Optimization of the CERN-SPS β-beam

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There are good physics reasons to prefer a higher γ β-beam at fixed ion flux:

J. Burguet-Castell et al, hep-ph/0312068

- Higher statistics (grows at least linearly with γ)
- More significant energy dependence of the oscillation signals when $\langle E_\nu \rangle \gg \boldsymbol{k}_{fermi}$
- Longer baselines $\longrightarrow$ larger matter effects

It is important to answer the question: how far physics-wise can we go with the CERN-SPS ?

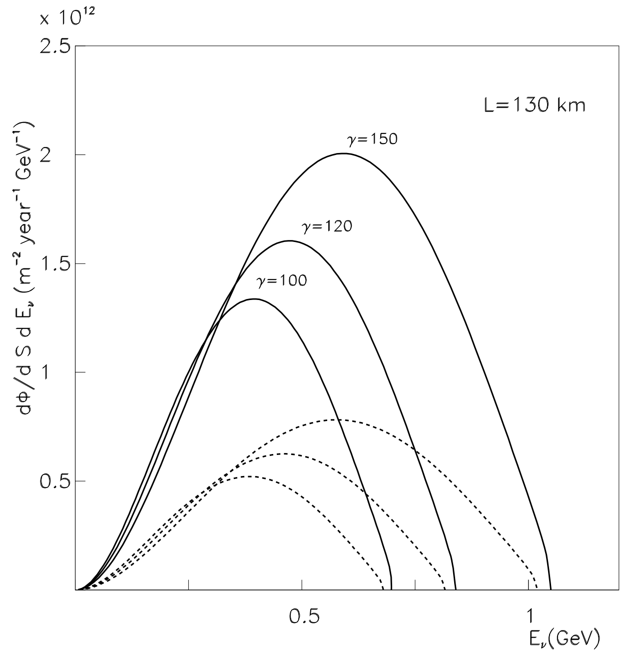
In our recent paper hep-ph/0503021 we did the following exercises:

Assuming a fixed ion flux at the CERN-SPS of: $N_{^6He} = 2.9 \times 10^{18}/year$ and $N_{^{18}Ne} = 1.1 \times 10^{18}/year$ and an integrated luminosity of 10 years

1. Optimization of γ at the CERN-SPS β-beam in two conditions:
   - at fixed $L = 130 km$
   - with a simultaneous optimization of L
2. Comparison of three setups
   - Setup 1: $\gamma_{optimal}$ at $L = 130 km$
   - Setup 2: $\gamma_{optimal}$ at $L_{optimal}$
   - Setup 3: $\gamma = 350$ at $L = 730 km$ (from hep-ph/0312068)

Flux

Energy spectra of ν_e (dashed) and $\bar{\nu}_e$(solid) at $L = 130$ km for $\gamma = 100, 120, 150$:



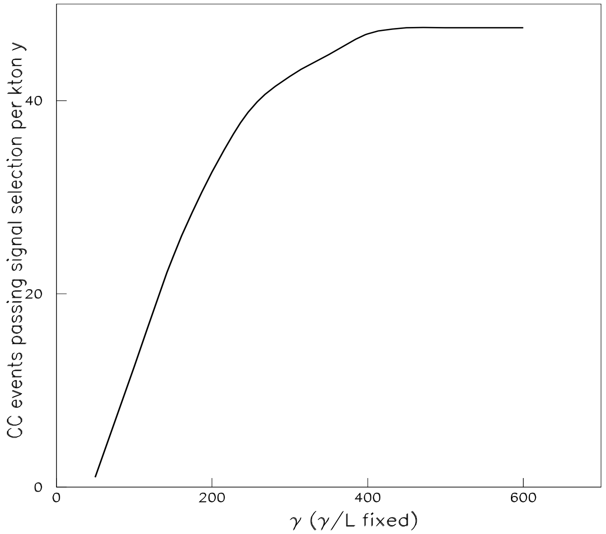
Number of charged-current events per kton-year, in the absence of oscillation, for the maximum acceleration of ^{6}**He** and ^{18}**Ne** at the CERN-SPS:

γ	$L(km)$	$\bar{\nu}_e$ CC	ν_e CC	$\langle E_\nu \rangle (GeV)$
150/250	300	22.8	115.6	0.58/0.94

Measurements

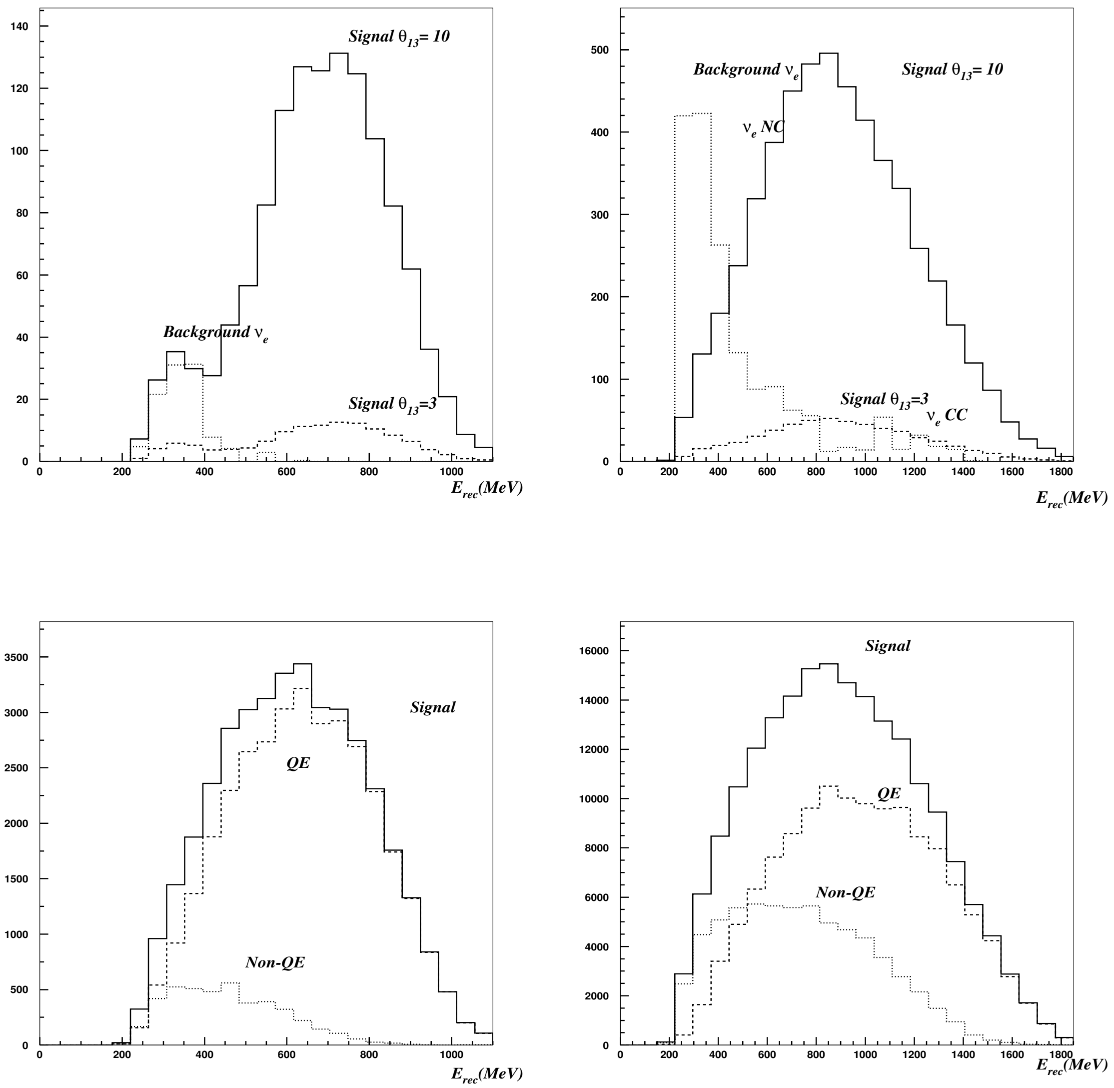
- Appearance signal: $\nu_e \longrightarrow \nu_\mu$ for ν and $\bar{\nu}$
  $\mu^\pm$ in the final state
- Disappearance signal: $\nu_e \longrightarrow \nu_e$ for ν and $\bar{\nu}$
  $e^\pm$ in the final state

Megaton water Cerenkov



The neutrino energy reconstructed only for quasi-elastic events: sensitivity will improve with γ until the inelastic region begins to dominate: $\gamma \leq 400$

Appearance signal



The non-QE contamination is significant $\longrightarrow$ matrices of background fractions and efficiencies to account for migrations

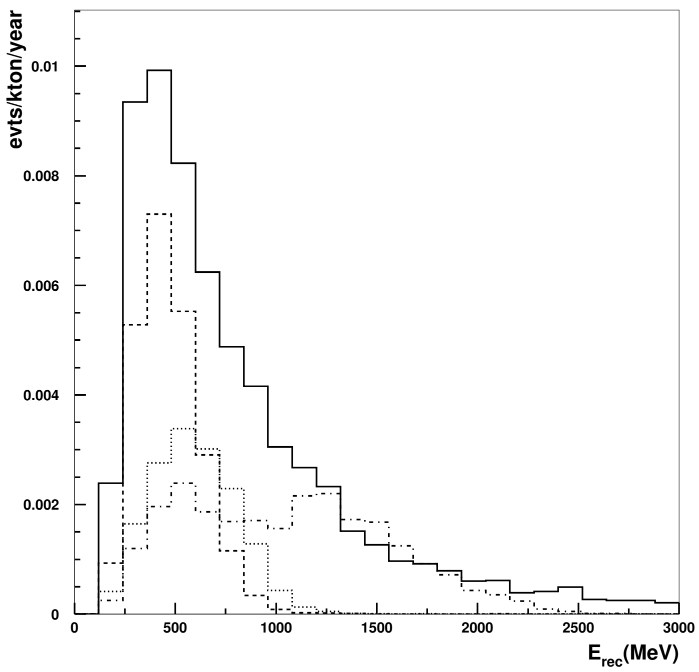
Bins: 0-500MeV and increments of 250MeV. For $\gamma = 350$ we cut the first bin.

Ion	γ	ϵ_{ij}^{app}	b_{ij}^{app}
^{6}He	120	$\begin{pmatrix} 0.65 & 0.18 & 0.071 \\ 0.03 & 0.54 & 0.33 \\ 0. & 0.016 & 0.34 \end{pmatrix}$	$\begin{pmatrix} 0.21 \times 10^{-3} & 0.30 \times 10^{-2} & 0.25 \times 10^{-2} \\ 0. & 0.68 \times 10^{-4} & 0.20 \times 10^{-3} \\ 0. & 0. & 0. \end{pmatrix}$
^{18}Ne	120	$\begin{pmatrix} 0.47 & 0.18 & 0.11 \\ 0.050 & 0.34 & 0.23 \\ 0.77 \times 10^{-3} & 0.30 \times 10^{-1} & 0.14 \end{pmatrix}$	$\begin{pmatrix} 0.73 \times 10^{-3} & 0.20 \times 10^{-2} & 0.30 \times 10^{-2} \\ 0.12 \times 10^{-3} & 0.55 \times 10^{-3} & 0.11 \times 10^{-2} \\ 0. & 0.39 \times 10^{-4} & 0.74 \times 10^{-3} \end{pmatrix}$
^{6}He	150	$\begin{pmatrix} 0.66 & 0.15 & 0.056 \\ 0.034 & 0.56 & 0.20 \\ 0. & 0.029 & 0.44 \end{pmatrix}$	$\begin{pmatrix} 0.22 \times 10^{-3} & 0.31 \times 10^{-2} & 0.24 \times 10^{-2} \\ 0. & 0.80 \times 10^{-4} & 0.12 \times 10^{-3} \\ 0. & 0. & 0. \end{pmatrix}$
^{18}Ne	150	$\begin{pmatrix} 0.47 & 0.16 & 0.082 \\ 0.054 & 0.34 & 0.16 \\ 0.84 \times 10^{-3} & 0.04 & 0.23 \end{pmatrix}$	$\begin{pmatrix} 0.78 \times 10^{-3} & 0.22 \times 10^{-2} & 0.35 \times 10^{-2} \\ 0.12 \times 10^{-3} & 0.66 \times 10^{-3} & 0.64 \times 10^{-3} \\ 0. & 0.47 \times 10^{-4} & 0.80 \times 10^{-3} \end{pmatrix}$

For the disappearance signal backgrounds are negligible and efficiencies quite high $80 - 90\%$ in lowest bin.

Atmospheric background

It is huge: out of $\sim 120\ \nu_\mu + \bar{\nu}_\mu$ per kton year expected 32 pass the signal selection cuts !



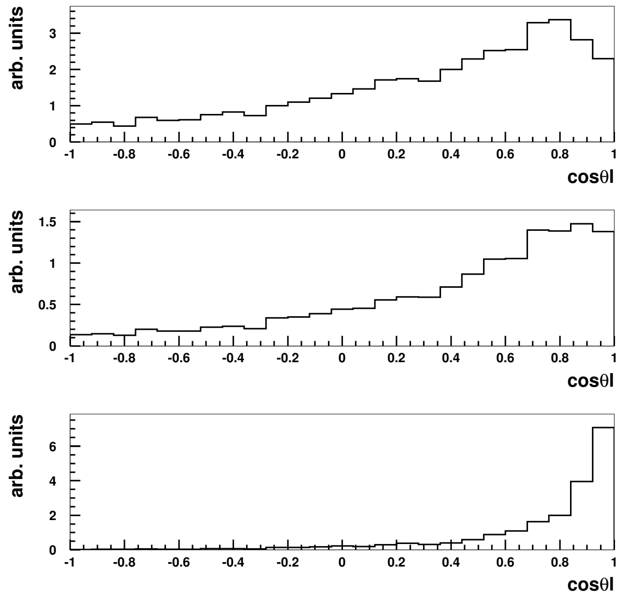
Energy spectrum of atmospheric $\nu_\mu + \bar{\nu}_\mu$ *background per kiloton-year, scaled down by a factor 1/500. Dashed, dotted and dash-dotted lines: energy spectrum of signal events per kiloton-year for* $\gamma = 120, 150$ *and* 350 *assuming* $\theta_{13} = 1^\circ$.

Extra handles:

- End-point of the β-beam spectrum
- Cut on the low-energy region
- Directional cut

γ	Selection	E_{max} cut	E_{min} cut	$\cos\theta_l$ cut
120	32	19	19	15
150	32	24	24	15
350	32	30	19	5

Cosine of the reconstructed neutrino-lepton scattering angle: $\gamma = 120$ (top), $\gamma = 150$ (middle) and $\gamma = 350$ (bottom)



Previously estimated $9ns$ bunches to reduce a factor 2×10^4: it is possible to live with a factor 5-10 less specially for the highest γ

Other systematics

We include also:

- 1% systematic error in the ratio $\sigma_\nu/\sigma_{\bar\nu}$
- 5% systematic error in the fidutial volume

Two new parameters are added to the fits: A, the global normalization and x, the relative normalization of anti-neutrino to neutrino rates:

$$\chi^2(\theta_{13},\delta,A,x) = 2\sum_{i,f=e,\mu}\left\{AxN_f^{i,+} - n_f^{i,+} + n_f^{i,+}\log\left(\frac{n_f^{i,+}}{AxN_f^{i,+}}\right)\right.$$
$$\left. + AN_f^{i,-} - n_f^{i,-} + n_f^{i,-}\log\left(\frac{n_f^{i,-}}{AN_f^{i,-}}\right)\right\} + \frac{(A-1)^2}{\sigma_A^2} + \frac{(x-1)^2}{\sigma_x^2}.$$

The minimization in the parameters A and x for fixed values of θ_{13} and δ is done analytically to leading order in the deviations $A-1$ and $x-1$ by solving the linearized system:

$$\frac{\partial\chi^2}{\partial A} = 0 \quad \frac{\partial\chi^2}{\partial x} = 0$$

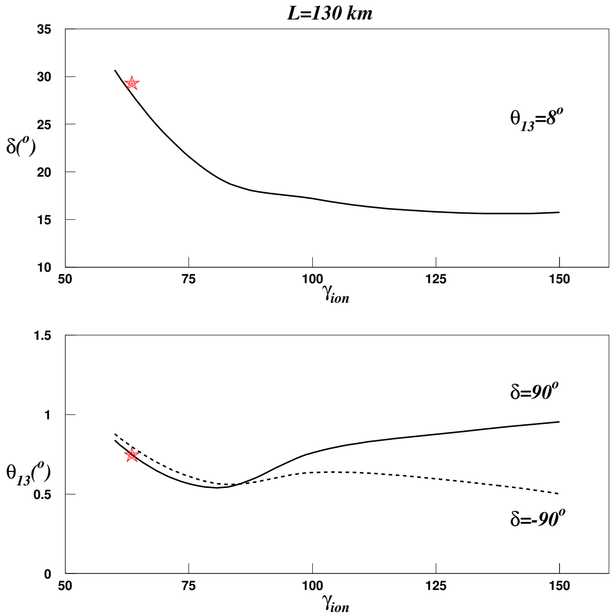
Physics Reach

- Sensitivity to CP violation: region on the plane (θ_{13}, δ) where the phase δ can be distinguished from both $\delta = 0^\circ$ and $\delta = 180^\circ$ for *any* best fit value of θ_{13}, at 99% confidence level or better.
- Sensitivity to θ_{13}: region on the plane (θ_{13}, δ) where the angle θ_{13} can be distinguished from $\theta_{13} = 0$ for any best fit value of δ, at 99% confidence level or better.

Unless otherwise specified, the following solar- and atmospheric-neutrino oscillation parameters are assumed:

$$\Delta m^2_{12} = 8.2 \times 10^{-5} eV^2 \quad \theta_{12} = 32^\circ \quad \Delta m^2_{23} = 2.2 \times 10^{-3} eV^2 \quad \theta_{23} = 45^\circ$$

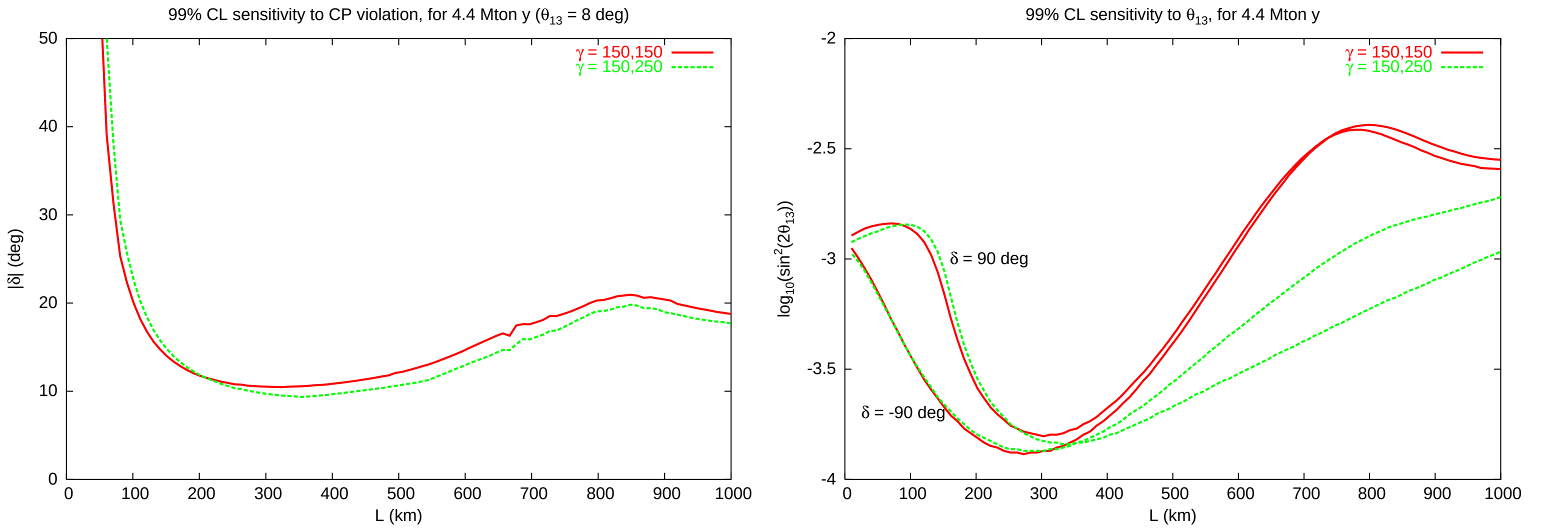
Optimal γ for $L = 130$km



γ-dependence of 99% confidence level δ sensitivity at $\theta_{13} = 8^\circ$ (top) and θ_{13} sensitivity (bottom) for $\delta = +90^\circ$ (solid) and $\delta = -90^\circ$ (dashed), assuming $L = 130$ km and $\gamma_{^6\mathrm{He}} = \gamma_{^{18}\mathrm{Ne}}$

There is a rather smooth dependence on γ only for $\gamma \leq 90 - 100$ and no gain for the asymmetric option

Optimal γ and L



Left: minimum value of $|\delta|$ distinguishable from 0 and 180° at 99% CL (for $\theta_{13} = 8^\circ$) vs. baseline for $\gamma = 150/150$ (red) and $\gamma = 150/250$ (green). Right: minimum value of θ_{13} distinguishable from 0 at 99% CL (for $\delta = 90^\circ$ and -90° as shown).

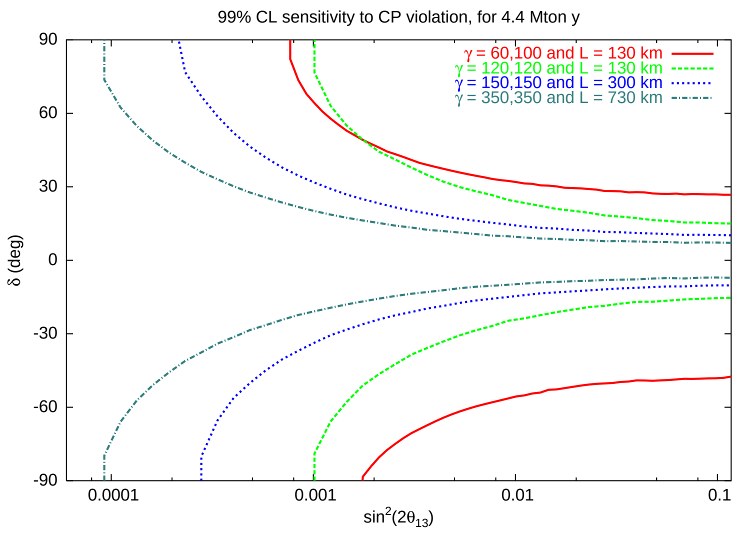
The symmetric option with $\gamma = 150$ and $L \sim 300$ km is close to optimal

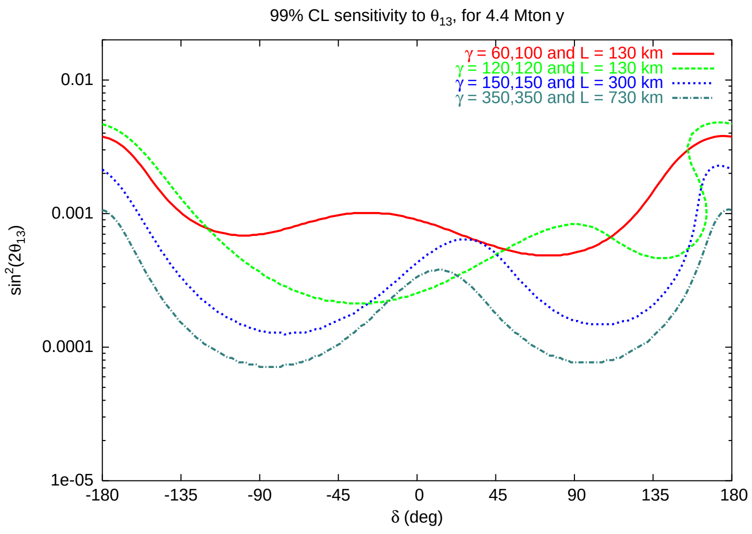
Comparison of three reference setups

- Setup I: $\gamma_{^6\text{He}} = \gamma_{^{18}\text{Ne}} = 120$ at $L = 130$ km
- Setup II: $\gamma_{^6\text{He}} = \gamma_{^{18}\text{Ne}} = 150$ at $L = 300$ km
- Setup III: $\gamma_{^6\text{He}} = \gamma_{^{18}\text{Ne}} = 350$ at $L = 730$ km (from hep-ph/0312068)

Intrinsic sensitivity to θ_{13} and δ

The solar and atmospheric parameters are fixed to their present best fit values and the discrete ambiguities are assumed to be resolved:



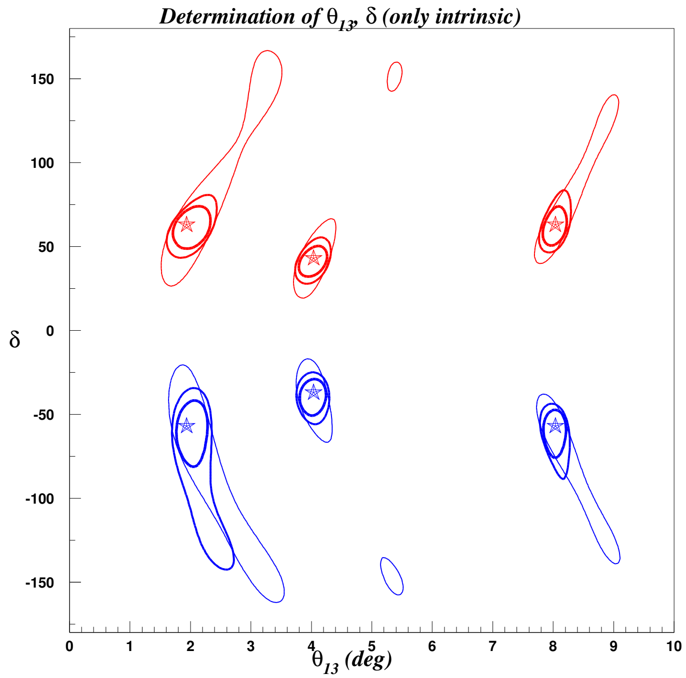


There is an two-fold ambiguity in the determination of the parameters (θ_{13}, δ) at fixed neutrino energy:

$$\begin{aligned} P_{\nu_e \nu_\mu}(\theta_{13}, \delta) &= Meas_1 \\ P_{\bar{\nu}_e \bar{\nu}_\mu}(\theta_{13}, \delta) &= Meas_2 \end{aligned} \tag{1}$$

- $(\theta_{13}^{fake}, \delta^{fake})$ depend on the neutrino energy strongly
- the fusion of the true and fake solutions enlarges the error a lot for certain values of δ
- the fake solution disappears with additional independent measurements: disappearance measurement, the silver channel, the golden channel at different E_ν/L

Appearance and disappearance:



Determination of (θ_{13}, δ) at 99% CL for Setups III (thicker line), II (intermediate) and I (thinner line)

Eight-fold degeneracy

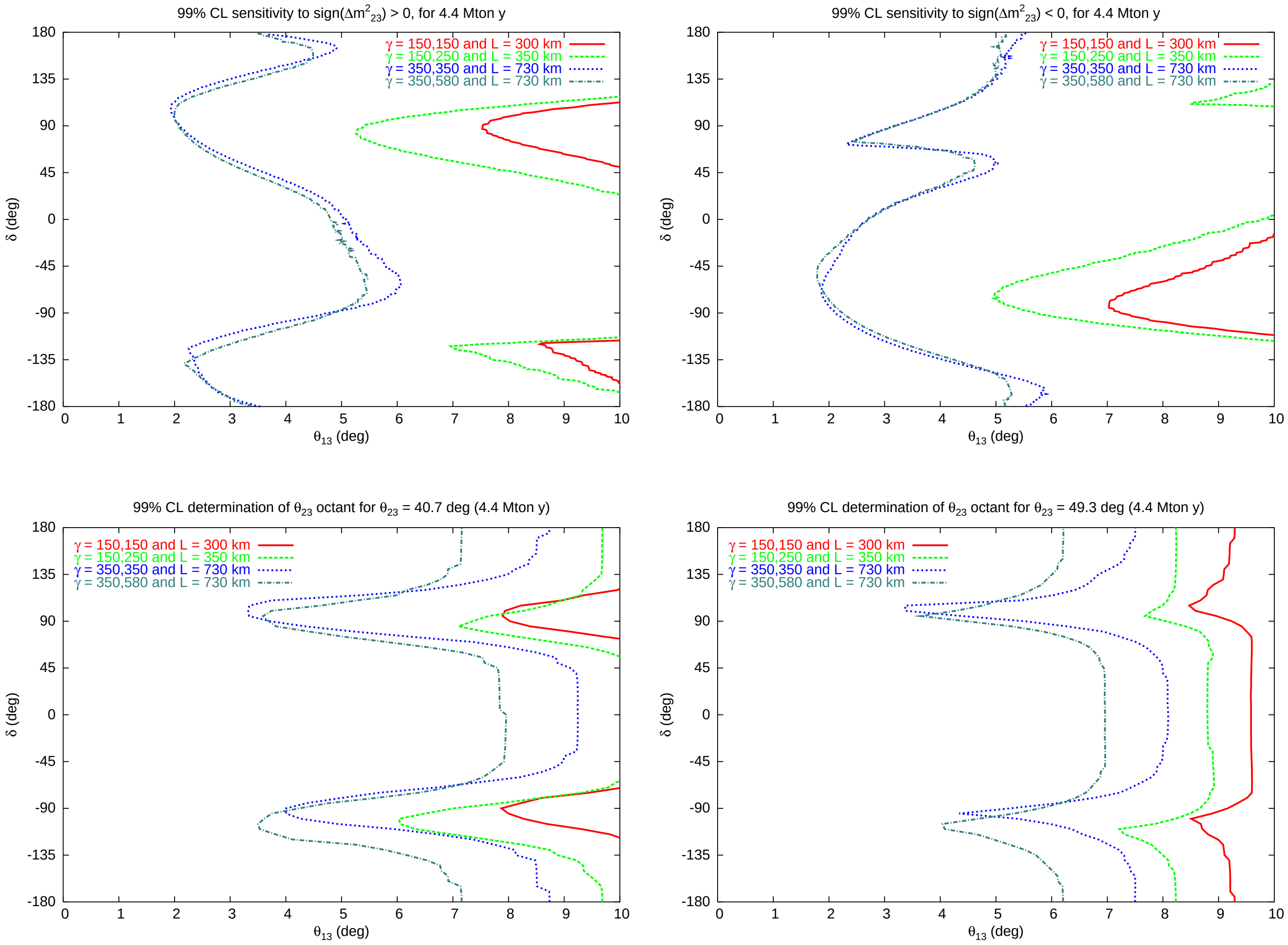
By the time any β-beam begins, it is probable that a number of uncertainties in the oscillation parameters besides θ_{13} and δ will remain, in particular: the discrete ambiguity in $\mathbf{sign}(\Delta m^2_{23})$ or the octant of θ_{23}.

Eight solutions: true and intrinsic fake solutions and three images of each for the wrong choice of $\mathbf{sign}(\Delta m^2_{23})$, octant or both.

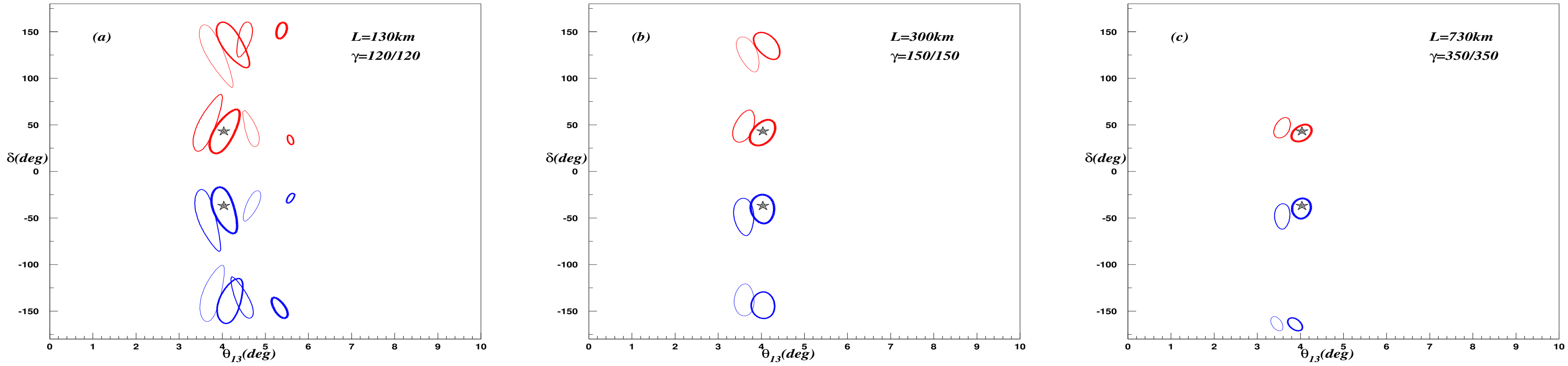
There are various possibilities:

- the β-beam can resolve them
- the β-beam cannot resolve them but they do not bias the measurement of (θ_{13}, δ).
- the β-beam cannot resolve them and they bias the measurement of (θ_{13}, δ).

When they can be resolved ?



And when they cannot be resolved ?



Solutions for (θ_{13}, δ) for the true values: $\delta = \pm 40^\circ$ and $\theta_{13} = 4^\circ$ in (a) Setup I, (b) Setup II and (c) Setup III without discrete ambiguities, with the sign, octant and mixed ambiguities ordered from thicker to thinner-line contours.

- Presence of the intrinsic solution or any of its images $\longrightarrow$ significant increase in the measurement errors of θ_{13} and δ for some values of δ.
- When only the images of the true solution survive, as in Setups II and III, they interfere with the measurement of θ_{13} and δ by mapping the true solution to another region of parameter space:

Wrong-sign: $\theta_{13} \longrightarrow \theta_{13}, \delta \longrightarrow \pi - \delta$

Wrong-octant: $\theta_{13} \longrightarrow \tan\theta_{23}\theta_{13} + \mathcal{O}(\Delta m^2_{12}), \quad \sin\delta \longrightarrow \cot\theta_{23}\sin\delta$

These solutions cannot overlap and fuse since they correspond to different choices of the discrete ambiguities $\longrightarrow$ a set of distinct measurements of θ_{13}, δ with different central values but similar errors

- In vacuum, CP violating solutions are mapped into CP violating solutions, therefore the effects of degeneracies on the exclusion plot for CP violation are often small, even when degeneracies are a problem.
- In matter, on the other hand, δ shifts in the fake solutions are enhanced by matter effects and for some central values of (θ_{13}, δ) the fake solutions may move closer to the CP conserving lines than the true solution, resulting in an apparent loss of sensitivity to CP violation.

Conclusions and outlook

- The physics potential of the CERN-SPS β-beam can be significantly improved by increasing γ (at least provided the ion flux can be maintained) and the baseline to $L \sim 300$km: is there such a baseline ?
- Only for rather high γ and baseline ($\gamma = 350$, $L = 730$km) can the discrete ambiguities be resolved in a significant region of parameter space: but combination with atmospheric and disappearance (e.g. T2K) can help
- The impact of the uncertainties in the atmospheric parameters can be very significant: the combination with the disappearance measurement in a superbeam is essential

Obviously other considerations are important from a practical point of view to define the optimal β-beam:

- Baseline: a viable site should exist (e.g. CERN-Frejus)
- Price: requires a serious and detailed design
  - a big part of the price is the megaton detector so the extra price for increasing γ should be compared to it
  - it would be important to consider the β-beam on its own and not under the constraints imposed by the superbeam: for example is the expensive 4Mwatt proton source really needed for the β-beam ?
- Competitors: how much better than other existing or planned projects can we do