Leptonic Mixing: beam/baseline options

The garden of forking paths

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The Flavour Problem

We have three families of elementary particles, with masses:

$$m_\nu \geq 0.05\,\mathrm{eV} \to m_t = 178\,\mathrm{GeV}$$

A thirteen order of magnitude hierarchy!

For a Standard Model of Particle Masses, we must understand the FLAVOUR MIXING both in quark and lepton sectors

$$\Downarrow$$

Measure of ALL parameters in the Mixing Matrices!

The leptonic mixing matrix, now

- $|\Delta m^2_{atm}| = (2.6 \pm 0.4) \cdot 10^{-3}$ eV^2
- $\Delta m^2_{sol} = (8.3 \pm 0.4) \cdot 10^{-5}$ eV^2
- $\sin^2\theta_{23} = (0.33 - 0.68)$ at 3σ
- $\sin^2\theta_{12} = (0.22 - 0.38)$ at 3σ
- $\sin^2\theta_{13} \leq 0.041$ at 3σ
- The sign of Δm^2_{atm}
- The θ_{23}-octant
- Is θ_{13} different from zero?
- Is δ different from zero?

Neutrino sources

- Natural sources:
  - ★ The Sun $\longrightarrow \nu_e$
  - ★ Cosmic rays $\longrightarrow \nu_e, \nu_\mu$
  - ★ Supernovae and relic SNs $\longrightarrow \nu_e, \nu_\mu, \nu_\tau$
  - ★ Geoneutrinos $\longrightarrow \nu_e$

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  - ★ Supernovae and relic SNs $\longrightarrow \nu_e, \nu_\mu, \nu_\tau$
  - ★ Geoneutrinos $\longrightarrow \nu_e$
- Man-made sources:
  - △ Reactors: $n \to pe\,\bar{\nu}_e$
  - △ Conventional beams: $\pi^\pm \to \mu^\pm\,\nu_\mu(\bar{\nu}_\mu)$
  - △ Neutrino Factory: $\mu^\mp \to e^\mp\,\nu_\mu, \bar{\nu}_e(\bar{\nu}_\mu, \nu_e)$
  - △ Beta beam: $^6\,\mathrm{He} \to \bar{\nu}_e$, $^{18}\,\mathrm{Ne} \to \nu_e$

Foreseen bounds on θ_{13}

EXP	θ_{13}	$\sin^2(2\theta_{13})$	$\sin^2\theta_{13}$
Global Fit	11.5°	0.157	0.041
BEAMS			
K2K	?	?	?
MINOS	6°	0.04	0.01
	$\to 8^\circ$	$\to 0.08$	$\to 0.02$
CNGS	5°	0.03	0.008
	$\to 7^\circ$	$\to 0.06$	$\to 0.015$

$P_{\mu\mu} \simeq$

$$1 - \sin^2(2\theta_{23})\sin^2\left[\frac{\Delta_{atm}L}{2}\right] + \mathcal{O}\left[\left(\frac{\Delta_{sol}}{\Delta_{atm}}\right)\sin\theta_{13}\cos\delta\right]$$

Sensitivity loss due to $(\theta_{13} - \delta)$-correlations

Foreseeable bounds on θ_{13}

EXP	θ_{13}	$\sin^2(2\theta_{13})$	$\sin^2\theta_{13}$
Global Fit	11.5°	0.157	0.041
REACT.			
Japan	4.5°	0.025	0.006
USA	3.5°	0.015	0.004
EU (D-CHOOZ)	5°	0.030	0.008

$$P_{ee} \simeq 1 - \sin^2(2\theta_{13})\sin^2\left[\frac{\Delta_{atm}L}{2}\right] + \mathcal{O}\left[\left(\frac{\Delta_{sol}}{\Delta_{atm}}\right)^2\right]$$

no sensitivity loss due to $(\theta_{13} - \delta)$-correlations

Foreseeable bounds on θ_{13} (2)

EXP	θ_{13}	$\sin^2(2\theta_{13})$	$\sin^2\theta_{13}$
Global Fit	11.5°	0.157	0.041
SBEAMS			
JHF-I (T2K)	2.2° $\to 3.3^\circ$	0.006 $\to 0.013$	0.0015 $\to 0.0030$
NUMI-OA (NOνA)	2° $\to 3.5^\circ$	0.005 $\to 0.015$	0.0010 $\to 0.0040$

Sensitivity loss due to $(\theta_{13} - \delta)$-correlations

Around 2012...

After the wave of conventional beams and first generation superbeams, and of high-power reactors experiments, we will know something more on the PMNS matrix:

- mass differences $\Delta m^2_{atm}, \Delta m^2_{sol}$ at some %;

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- the value of θ_{13}, if large;

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- the sign of Δm^2_{23}, if lucky.

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- ▷ mixing angles θ_{12}, θ_{23} at some %;
- ▷ the value of θ_{13}, if large;
- ▷ the sign of Δm^2_{23}, if lucky.

Precision measurements of LEPTONIC MIXING will start with the next-to-next generation experiments, using Neutrino Factory and/or Beta Beam. However....

An intermediate phase?

After T2K and NOνA, we will face a forking path:

- ★ $\nu_\mu \to \nu_e$ oscillation has been observed!
  A good option: increase detector mass,
  same source: T2-HK or SPL+UNO
  (really a good option?)
- No signal has been observed: $\theta_{13} \leq 3^\circ - 4^\circ$!
  Go to new sources:
  Neutrino Factory or the Beta-Beam.

I will use the CERN SPL project to illustrate the problems we face to measure (θ_{13}, δ) in the intermediate phase.
T2-HK gives similar results.

Appearance Signal at a SB

$$\pi^+ \rightarrow \begin{cases} \mu^+ \rightarrow \bar{\nu}_\mu, \nu_e \rightarrow e^- & \textit{Background} \\ \nu_\mu \rightarrow \nu_e \rightarrow e^- & \textit{Signal} \end{cases}$$

The oscillation probability is

$$P^{\pm}_{\mu e} \simeq X_\pm \sin^2(2\,\theta_{13})$$

$$+Y_\pm \cos\left(\delta \pm \frac{\Delta_{atm} L}{2}\right) \cos\theta_{13} \sin(2\,\theta_{13})$$

$$+Z + \ldots$$

The (θ_{13}, δ) correlation

The number of signal electrons is:

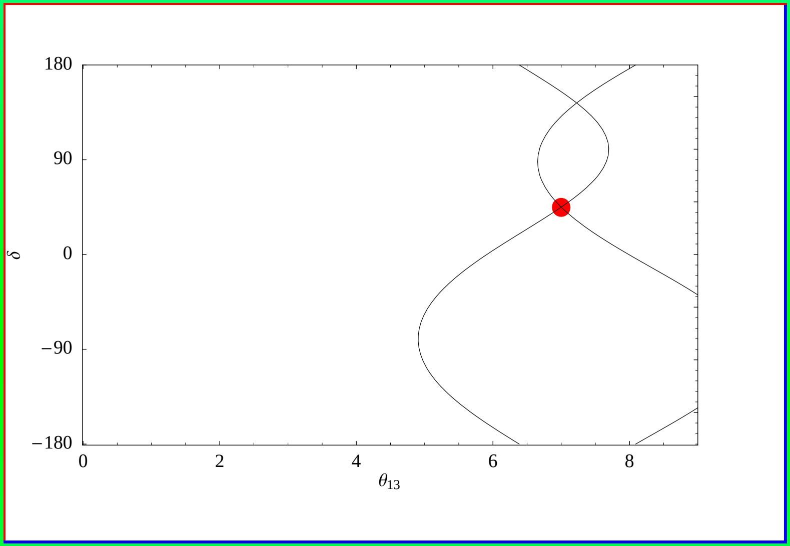
$$N_{e^-}(\bar{\theta}_{13}, \bar{\delta}) = \left\{ \epsilon_e \otimes \sigma_{\nu_e} \otimes P^{+}_{\mu e}(\bar{\theta}_{13}, \bar{\delta}) \otimes \Phi_{\nu_\mu} \right\}_{E}^{E+\Delta E}$$

$$N^i_{\pm}(\bar{\theta}_{13}, \bar{\delta}) = N^i_{\pm}(\theta_{13}, \delta)$$

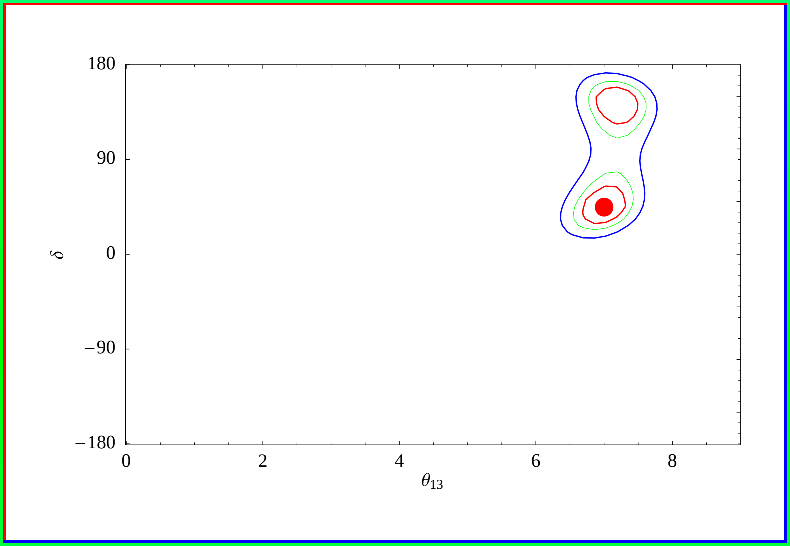
By changing (θ_{13}, δ) accordingly,
curves are drawn in the (θ_{13}, δ) plane.

Degeneracy in (θ_{13}, δ) at the SPL

2 years for π^+ and 8 years for π^-



$\Rightarrow$



L = 130 Km, $\bar{E}_{\nu_\mu} = 0.27$ GeV, $\bar{E}_{\bar{\nu}_\mu} = 0.25$ GeV

Input parameters: $\bar{\theta}_{13} = 7^\circ, \bar{\delta} = 45^\circ$

The (θ_{13}, δ) correlation (2)

The number of signal electrons is:

$$N_{e^-}(\bar\theta_{13}, \bar\delta) = \left\{ \epsilon_e \otimes \sigma_{\nu_e} \otimes P^{+}_{\mu e}(\bar\theta_{13}, \bar\delta) \otimes \Phi_{\nu_\mu} \right\}_{E}^{E+\Delta E}$$

$$N^i_\pm(\bar\theta_{13}, \bar\delta, \bar s_{atm}, \bar s_{oct}) = N^i_\pm(\theta_{13}, \delta, s_{atm}, s_{oct})$$

where

$$\begin{cases} s_{atm} &= sign(\Delta m^2_{atm}) = \pm 1 \\ s_{oct} &= sign(\tan 2\theta_{23}) = \pm 1 \end{cases}$$

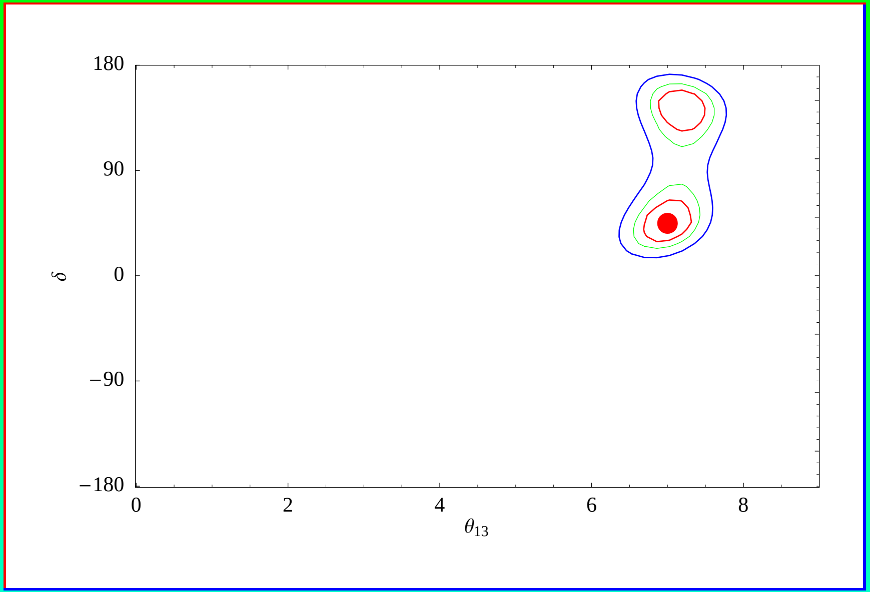
Of other clones

As a first step:

- $\theta_{23} = 45^\circ$
- Sign of Δ_{atm} fixed

J. Burguet-Castell *et al.*, hep-ph/0103258

The intrinsic clone



Of other clones

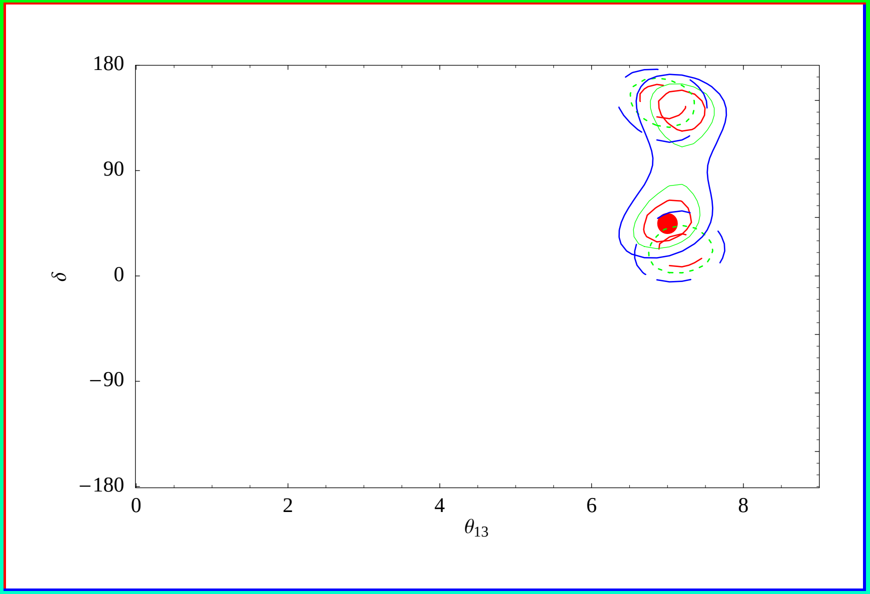
As a third step:

- $\theta_{23} = 45^\circ$
- Sign of Δ_{atm} variable

H. Minakata, H. Nunokawa, hep-ph/0108085

One more ambiguity:

- the sign clone

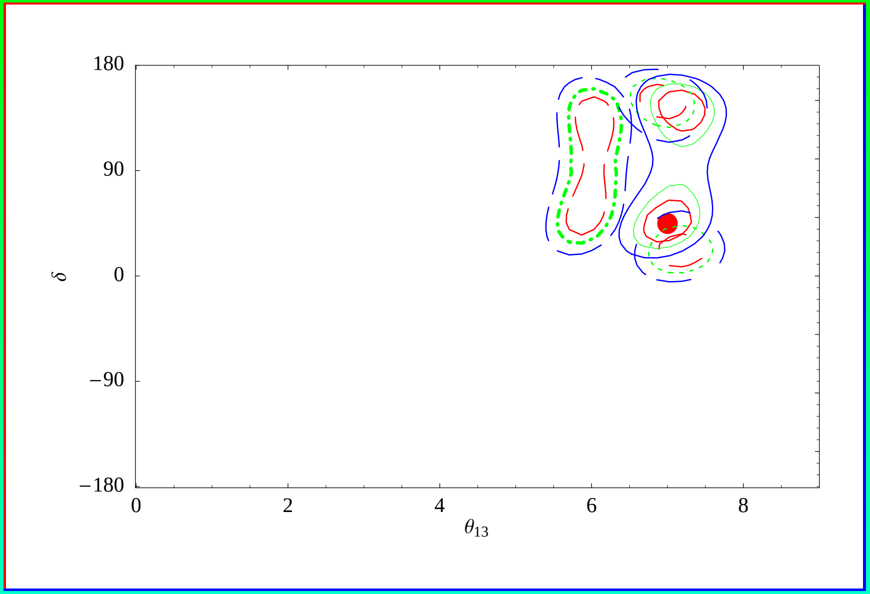


Of other clones

As a second step:

- ▷ $\theta_{23} \neq 45^\circ$
- ▷ Sign of Δ_{atm} fixed

G.L. Fogli, E. Lisi, hep-ph/9604415



Two more ambiguities:

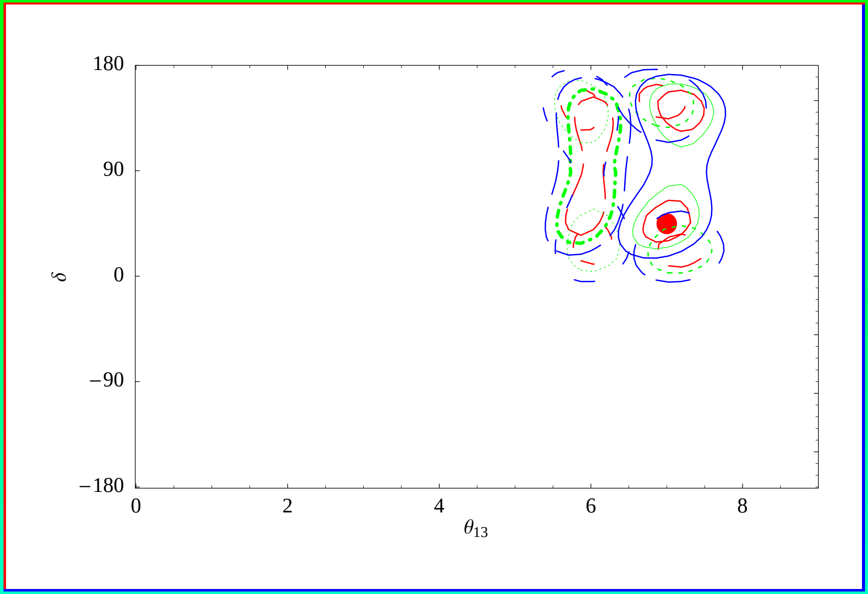
- ▷ the octant clone
- ▷ the sign clone

Of other clones

As a fourth step:

- ▷ $\theta_{23} \neq 45^\circ$
- ▷ Sign of Δ_{atm} variable

V. Barger *et al.*, hep-ph/0112119

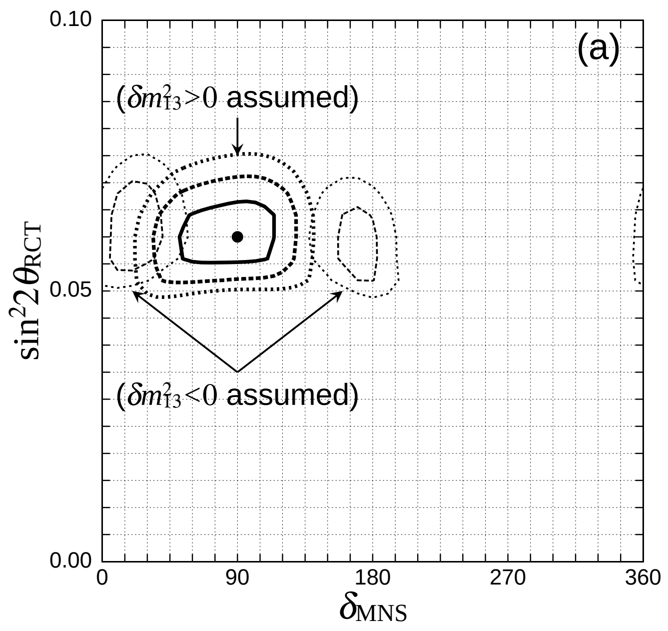


Three more ambiguities:

- ▷ the octant clone
- ▷ the sign clone
- ▷ the mixed clone

The same at T2-HK

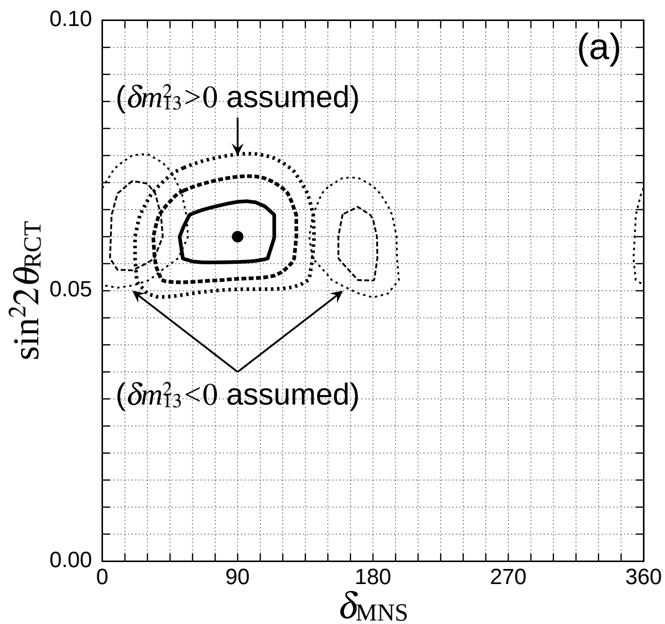
The sign degeneracy



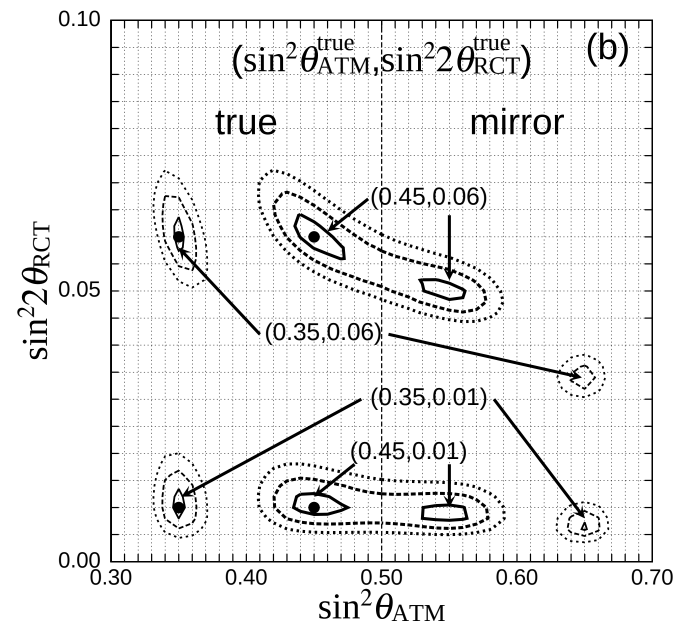
K. Hagiwara, hep-ph/0410229

The same at T2-HK

The sign degeneracy



The octant degeneracy



K. Hagiwara, hep-ph/0410229

The Ultimate Setup

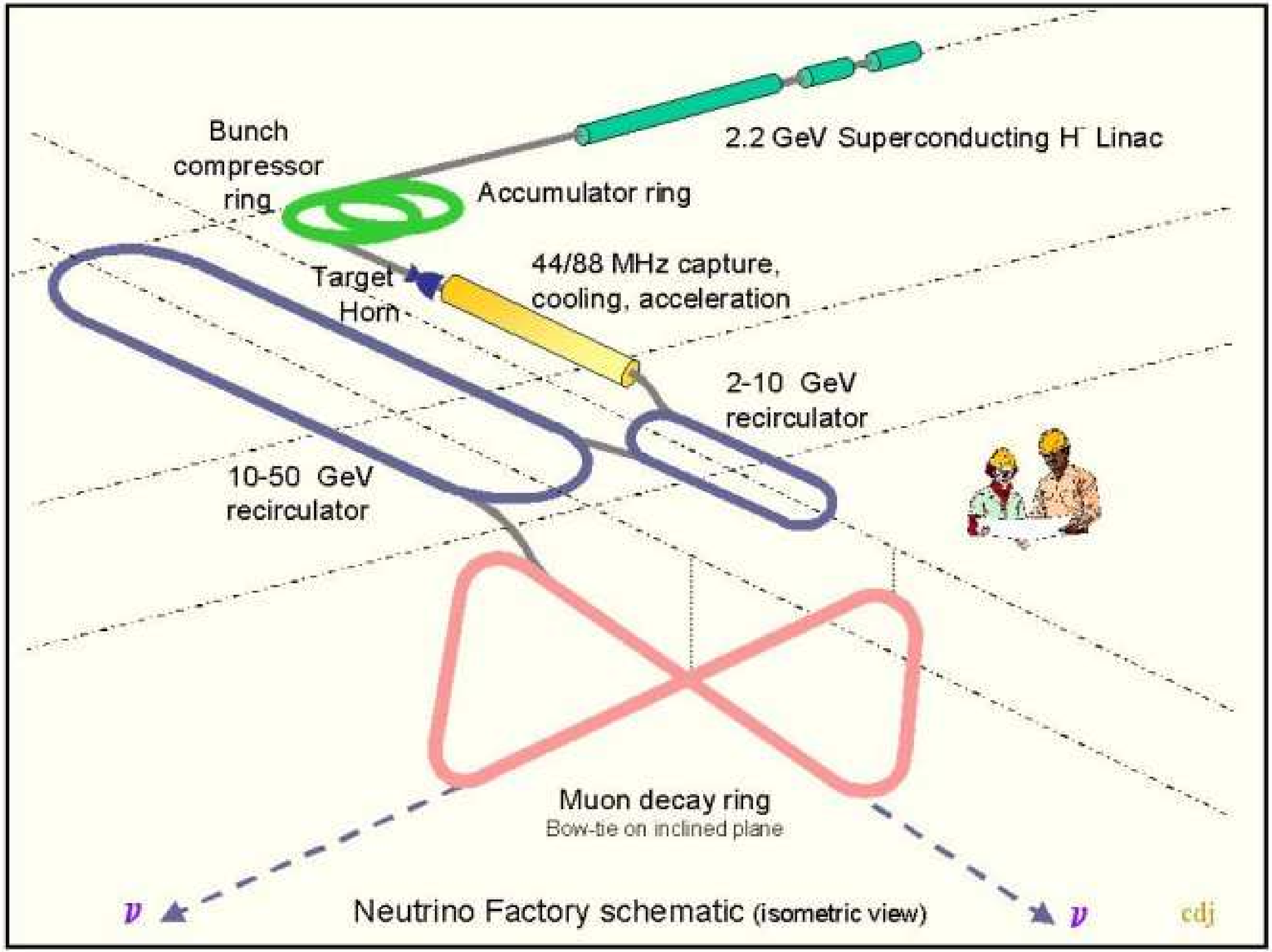
Conventional (super)beams alone are not enough.
We must consider NEW FACILITIES.

- ▷ The Neutrino Factory
  - one SuperBeam facility
  - two μ-decay tunnels

A. Donini, hep-ph/0310014; NuFact03, New York

Caveat: this study must be updated.

The Neutrino Factory at CERN



The ν-factory/detectors setup

CERN design for a 2.2 GeV superbeam
and a 50 GeV Neutrino Factory

- NF: 40 Kton Magnetized iron detector (MID)
  $L = 2810$ Km (Canary Islands)

  A. Cervera *et al.*,

  Nucl. Instr. Meth. A 451 (2000) 123; NuFact99, Lyon
- NF: 4 Kton Emulsion Cloud Chamber (ECC)
  $L = 732$ Km (Gran Sasso) or $L = 2810$ Km

  D. Autiero *et al.*, hep-ph/0305185; NuFact03, New York
- SB: 400 Kton Water Cherenkov (WC)
  $L = 130$ Km (Frejus)

  A. Blondel *et al.*,

  Nucl. Instr. Meth. A 503 (2001) 173; NuFact01, Tsukuba

The Golden channel: ν-factory

A. Cervera *et al.*, hep-ph/0002108

$$\mu^+ \to \begin{cases} e^+ \\ \bar{\nu}_\mu \to \mu^+ & \textit{Background} \\ \nu_e \to \nu_\mu \to \mu^- & \textit{Signal} \end{cases}$$

The oscillation probability is

$$P^{\pm}_{e\mu} = X_\pm \sin^2(2\,\theta_{13})$$

$$+Y_\pm \cos\left(\delta \mp \frac{\Delta_{atm} L}{2}\right) \cos\theta_{13} \sin(2\,\theta_{13})$$

$$+Z + \ldots$$

The Silver channel: ν-factory

A. Donini, D. Meloni and P. Migliozzi, hep-ph/0206034

$$\mu^+ \rightarrow \begin{cases} e^+ \\ \bar{\nu}_\mu \rightarrow \mu^+ \\ \nu_e \rightarrow \nu_\tau \rightarrow \tau^- \rightarrow \mu^- \end{cases}$$

The oscillation probability is

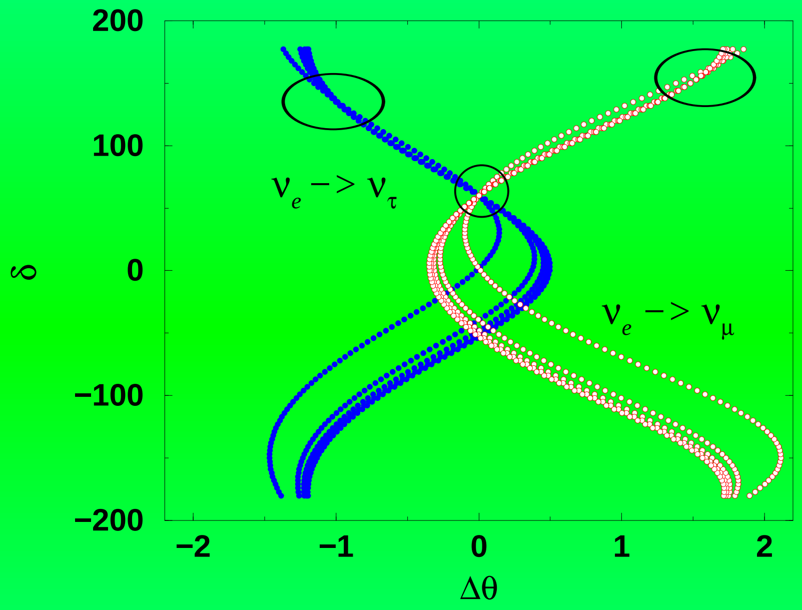
$$P^{\pm}_{e\tau} = X^\tau_\pm \sin^2(2\,\theta_{13})$$

$$-Y^\tau_\pm \cos\left(\delta \mp \frac{\Delta_{atm} L}{2}\right) \cos\theta_{13} \sin(2\,\theta_{13})$$

$$+Z^\tau + \ldots$$

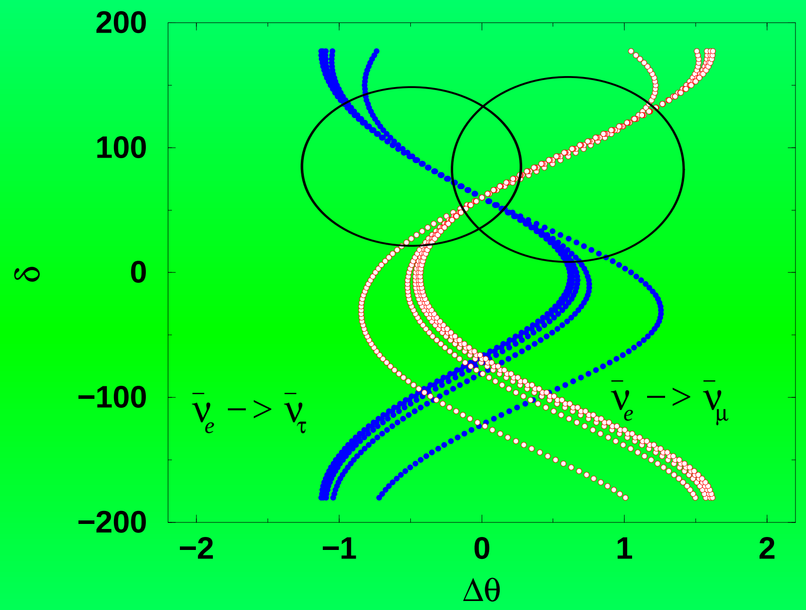
The intrinsic clones

$L = 732$ Km



Neutrinos

$L = 732$ Km



Antineutrinos

$$\begin{cases} \bar{\theta}_{13} & = & 5^\circ \\ \bar{\delta} & = & 90^\circ \end{cases}$$

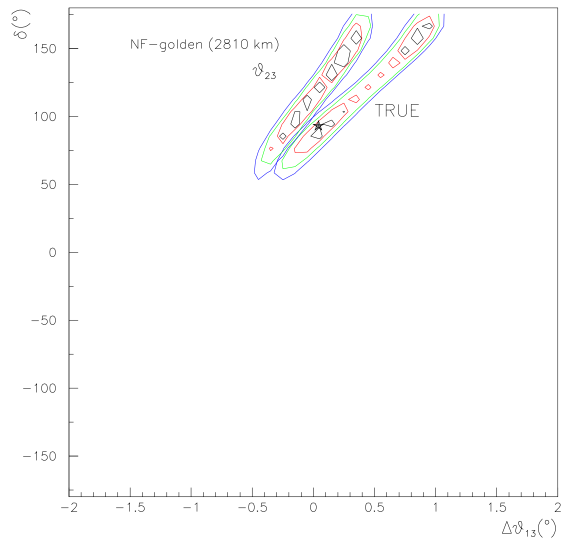
$$\Delta\theta = \theta_{13} - \bar{\theta}_{13}$$

One detector

Consider the NuFact golden channel:
best option for one detector, with baseline $L = 2810$
(no sign degeneracies for $\theta_{13} \geq 1^\circ$).

A. Cervera *et al.*, hep-ph/0002108

- 40 Kton MID



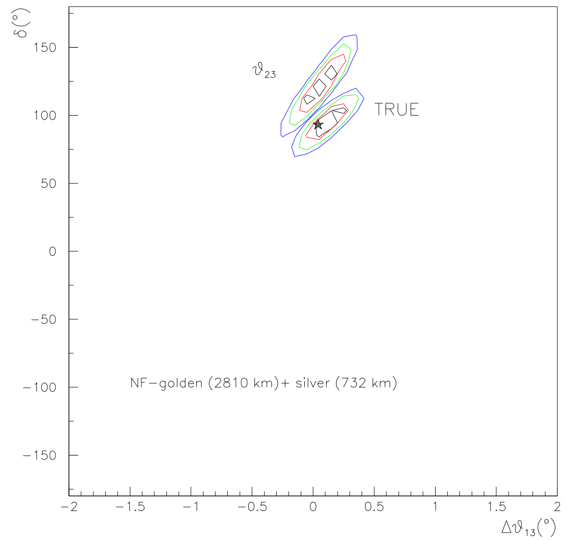
$\bar{\theta}_{13} = 2^\circ \; \bar{\delta} = 90^\circ$

Two detectors

You can now add a second detector.
We can take advantage of the NuFact silver channel...

A. Donini *et al.*, hep-ph/0206034

- 40 Kton MID
- 4 Kton ECC



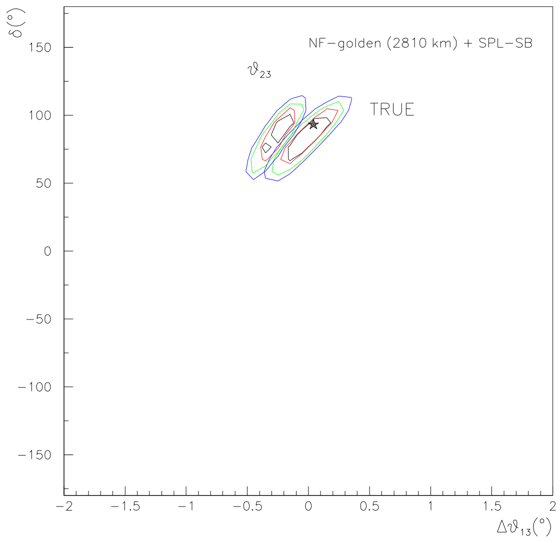
$$\bar{\theta}_{13} = 2^\circ \; \bar{\delta} = 90^\circ$$

Two detectors

... or of the Superbeam-driven water Cherenkov.

J. Burguet-Castell *et al.*, hep-ph/0207080

- 40 Kton MID
- 400 Kton WC



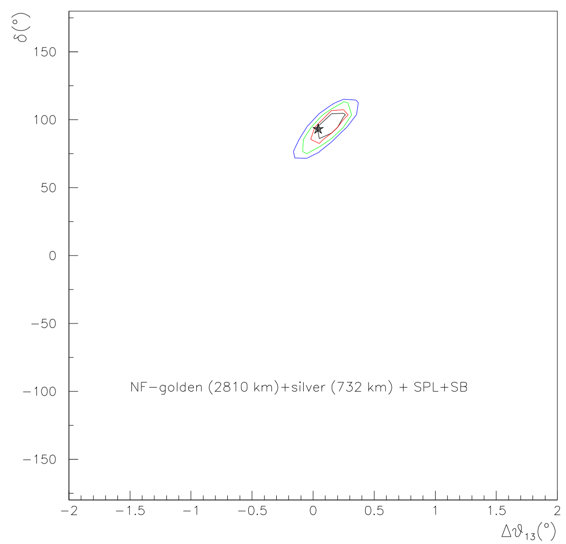
$$\bar{\theta}_{13} = 2° \ \bar{\delta} = 90°$$

The Three Detectors

However, the very best possibility is
to combine the three detectors in their FULL GLORY.

A. Donini, hep-ph/0310014

- 40 Kton MID
- 4 Kton ECC
- 400 Kton WC



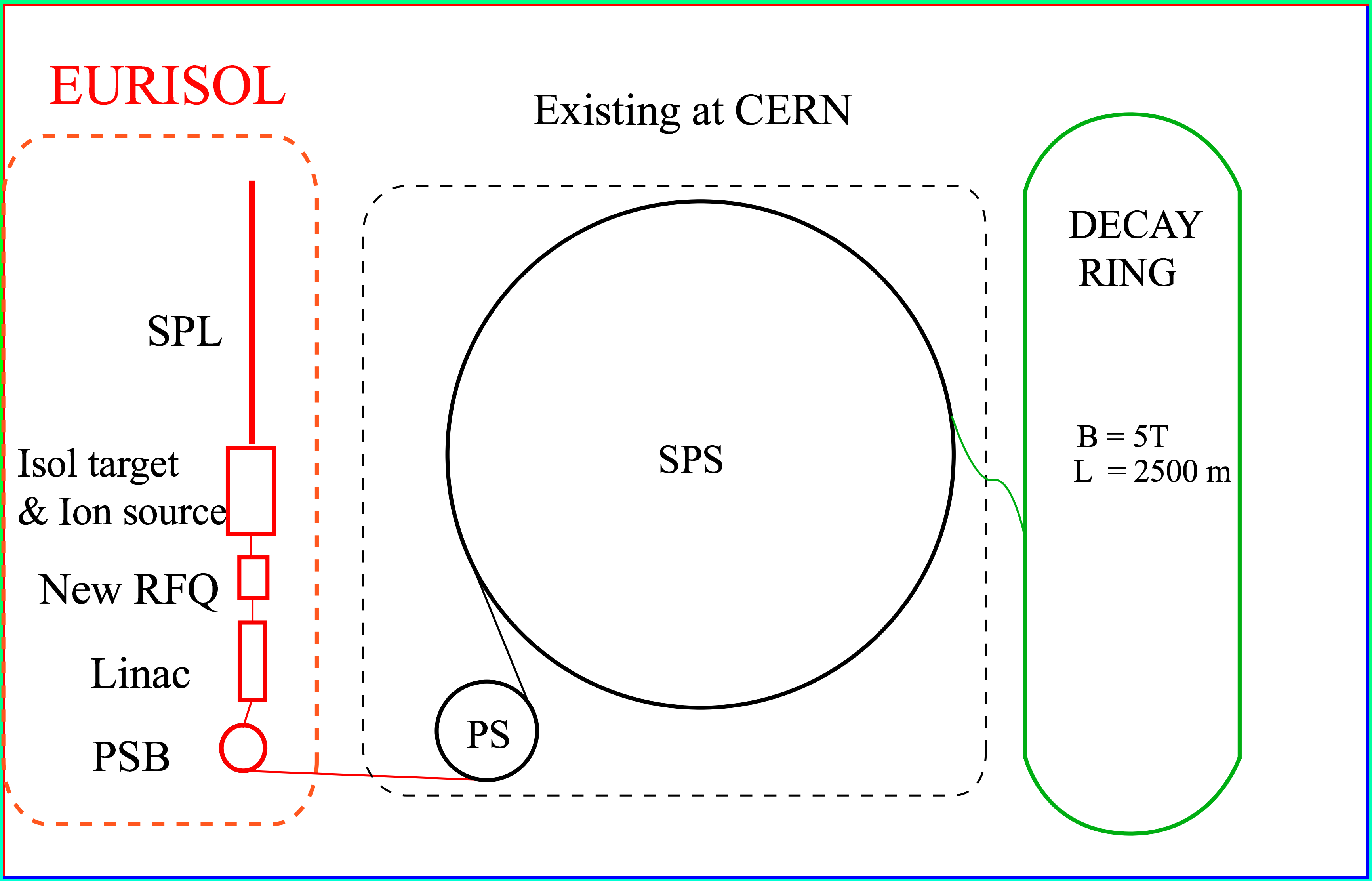
$$\bar{\theta}_{13} = 2^\circ \ \bar{\delta} = 90^\circ$$

Alternatives?

- The Beta Beam
  - very low-γ BB
    C. Volpe, hep-ph/0303222, hep-ph/0403293
  - low-γ BB plus the SPL
    J. Bouchez *et al.*, hep-ph/0310059
  - medium-γ BB: ions cocktail
    J. Burguet-Castell *et al.*, hep-ph/0312068
  - high-γ BB vs the NuFact
    J. Burguet-Castell *et al.*, hep-ph/0312068
  - very high-γ BB
    P. Migliozzi and F. Terranova, hep-ph/0405081

I will not cover options (1) and (5).

The Beta-Beam at CERN



The Golden channel: β-beam

$$^{18}\mathrm{Ne} \rightarrow \begin{cases} e^+ \\ ^{18}\mathrm{F} \\ \nu_e \rightarrow \nu_\mu \rightarrow \mu^- \end{cases} \qquad Signal$$

The oscillation probability is

$$P_{e\mu}^{\pm} = X_\pm \sin^2(2\,\theta_{13})$$

$$+Y_\pm \cos\left(\delta \mp \frac{\Delta_{atm} L}{2}\right) \cos\theta_{13} \sin(2\,\theta_{13})$$

$$+Z + \ldots$$

The SPL and low-γ Beta Beam

CERN design for 2.2 GeV superbeam
and a low-γ β-beam:
$\gamma = 60$ for ^{6}He;
$\gamma = 100$ for ^{18}Ne

- 440 Kton Water Cherenkov (WC)
  $L = 130$ Km (Frejus)

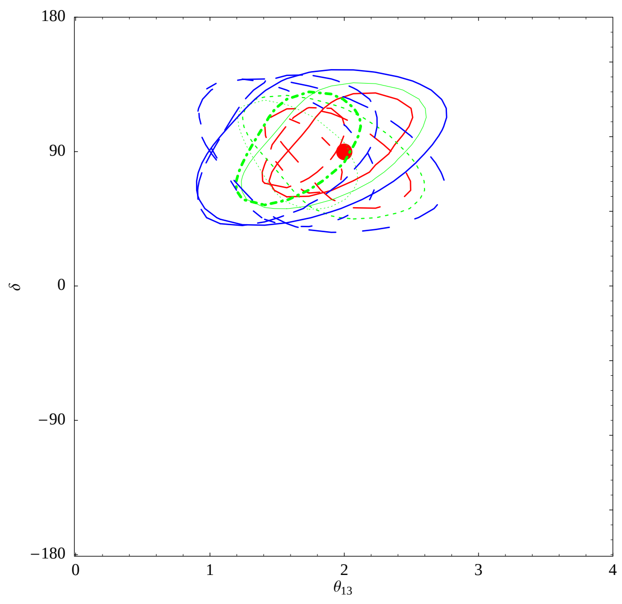
  UNO Collaboration, hep-ex/0005046;
  D. Casper, Nucl. Phys. Proc. Suppl. 112 (2002) 161.

The SPL and low-γ Beta Beam

Consider the $\nu_e \to \nu_\mu$ at the BB:
one massive Water Cherenkov, with baseline $L = 130$

J. Bouchez *et al.*, hep-ph/0310059

- 440 Kton WC-BB

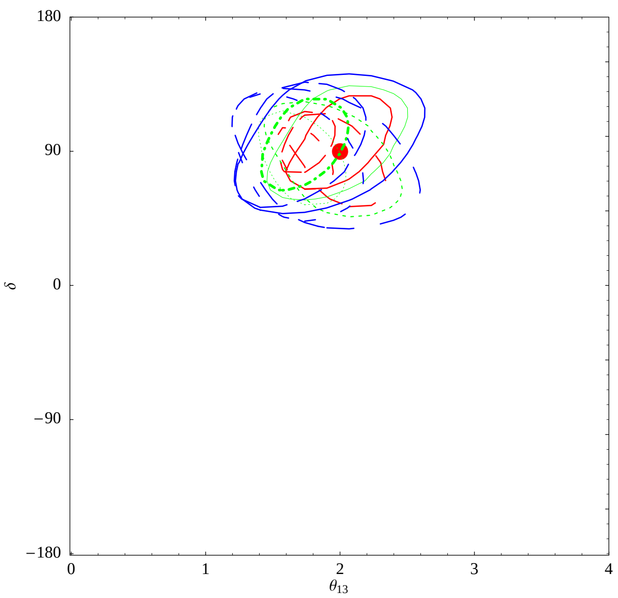


$\bar{\theta}_{13} = 2^\circ\ \bar{\delta} = 90^\circ$

The SPL and low-γ Beta Beam

You can now add $\nu_\mu \to \nu_e$ at the SPL:
same detector, same baseline

- 440 Kton WC-BB
- 440 Kton WC-SPL

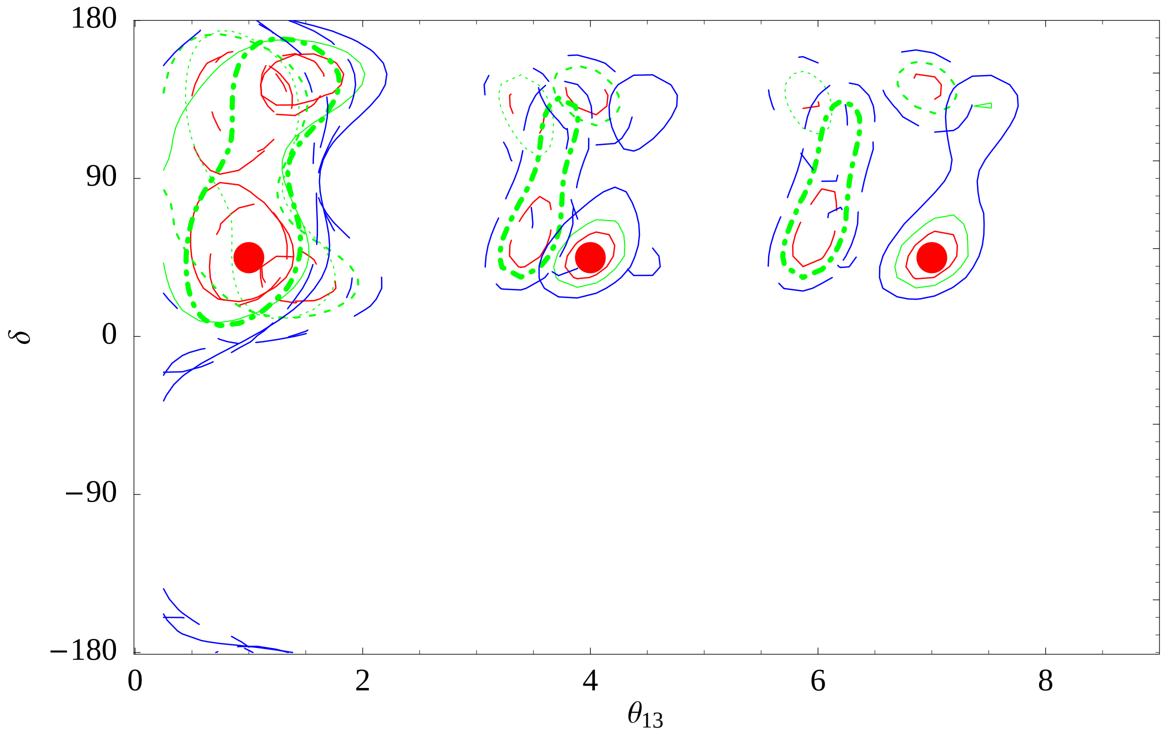


$$\bar{\theta}_{13} = 2^\circ \ \bar{\delta} = 90^\circ$$

The SPL and low-γ Beta Beam

This is the general situation for $\delta \neq 90°$.

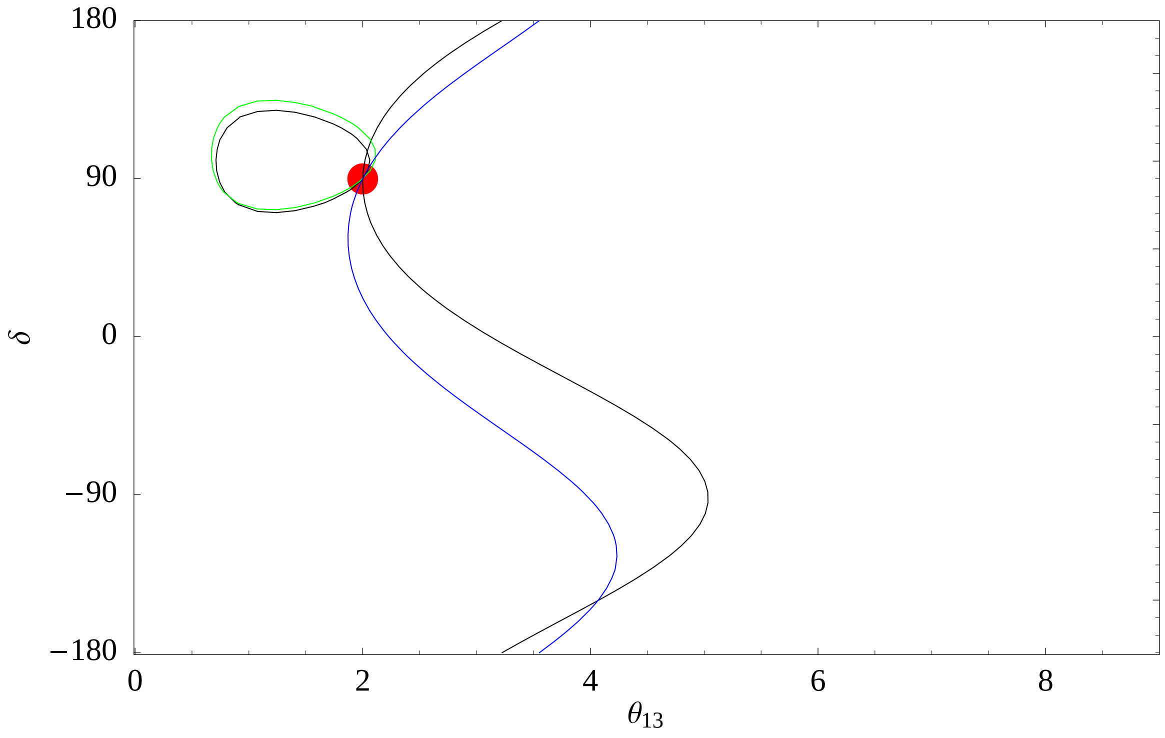
A. Donini *et al.*, hep-ph/0406132



$\bar{\theta}_{13} = 1°, 4°, 7°$ $\bar{\delta} = 45°$

The SPL and low-γ Beta Beam

Unfortunately, there is NO SYNERGY:
same detector, same baseline, SAME ENERGY!



$$\bar{\theta}_{13} = 2^\circ \ \bar{\delta} = 90^\circ$$

The medium-γ Beta Beam

Using an upgraded SPS or the LHC, we could increase the energy:

$\gamma = 350$ for ^{6}He;

$\gamma = 580$ for ^{18}Ne

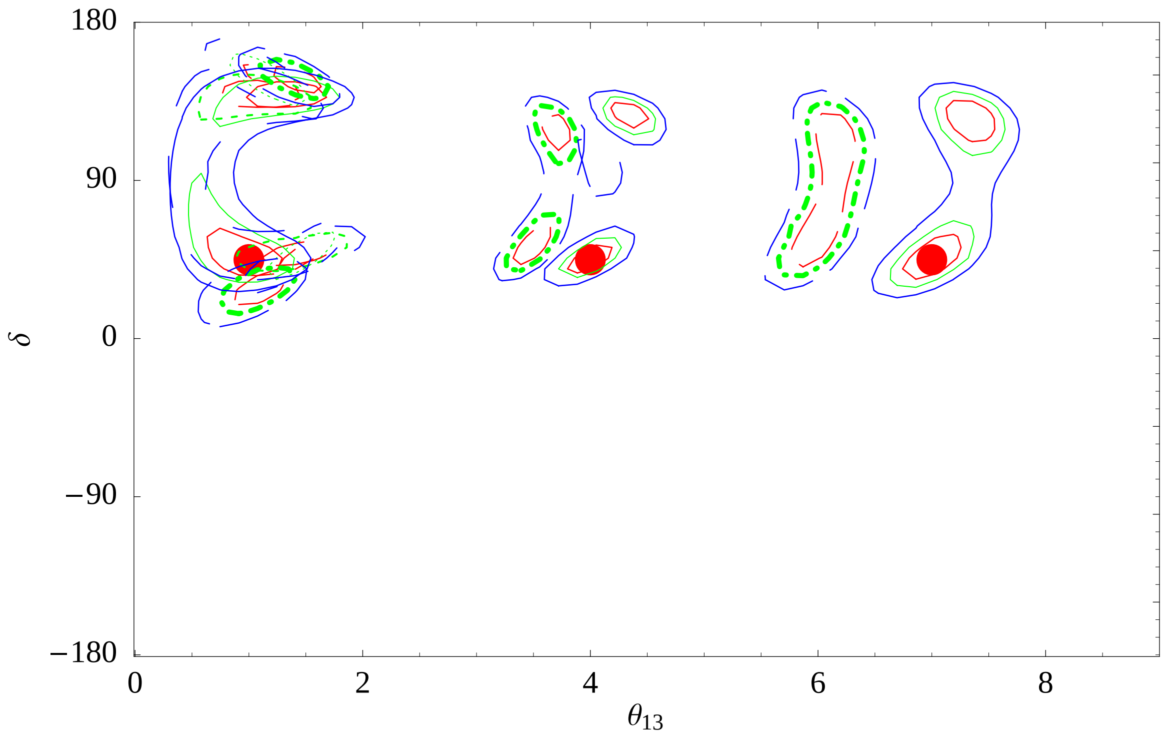
The same detector:

- 440 Kton Water Cherenkov (WC)
  $L = 732$ Km (Gran Sasso or Soudan)
  UNO Collaboration, hep-ex/0005046;
  D. Casper, Nucl. Phys. Proc. Suppl. 112 (2002) 161.

In this case, energy resolution can be used

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

The medium-γ Beta Beam

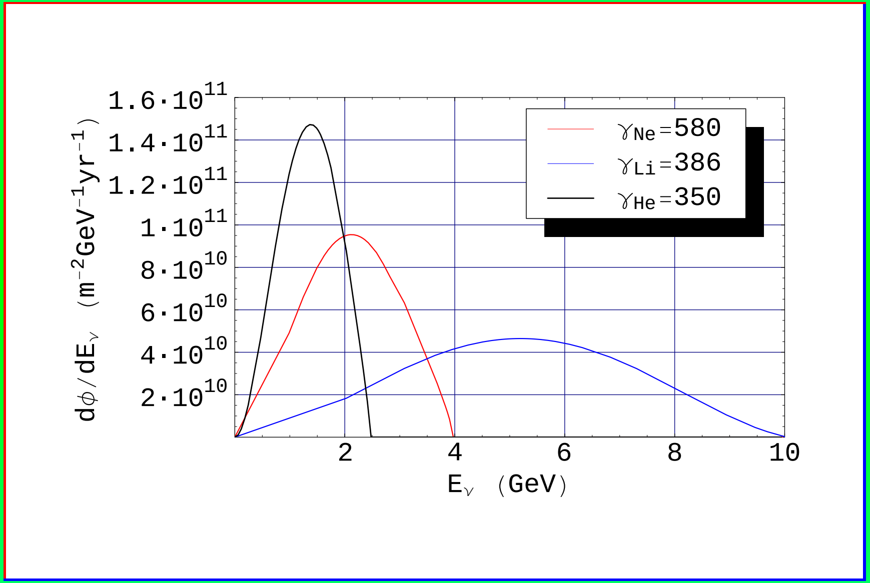


$$\bar{\theta}_{13} = 1^\circ, 4^\circ, 7^\circ \; \bar{\delta} = 45^\circ$$

The medium-γ Beta Beam

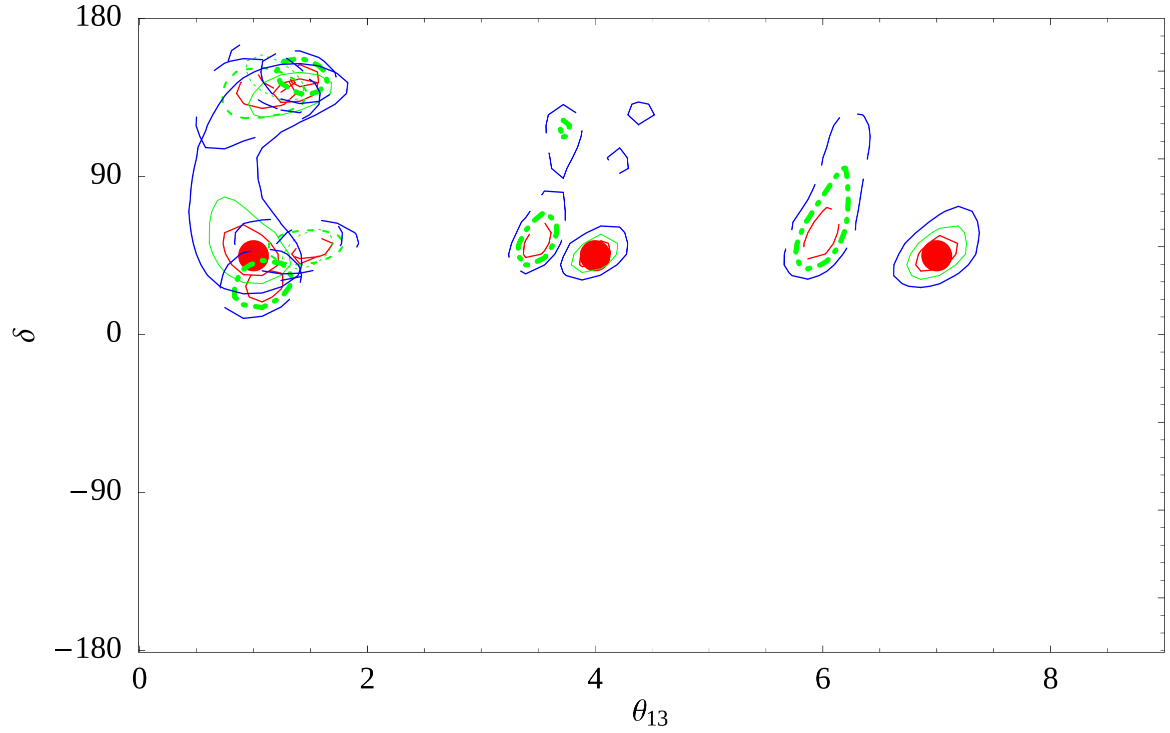
^8Li is a good alternative to ^6He:
higher production rate, same lifetime.

- low-γ:
  higher statistics
- medium-γ:
  complementarity



AD, E. Fernández-Martínez, S. Rigolin.

The ions cocktail at medium-γ



$\bar{\theta}_{13} = 1^\circ, 4^\circ, 7^\circ \; \bar{\delta} = 45^\circ$

- five years with $\gamma_{^6He} = 350$; $\gamma_{^{18}Ne} = 580$;
- five years with $\gamma_{^8Li} = 386$; $\gamma_{^{18}Ne} = 580$.

The high-γ Beta Beam

If (using the LHC?) we achieve the energy:
$\gamma = 1500$ for ^{6}He; $\gamma = 2500$ for ^{18}Ne
then we can use both the golden and silver channels:

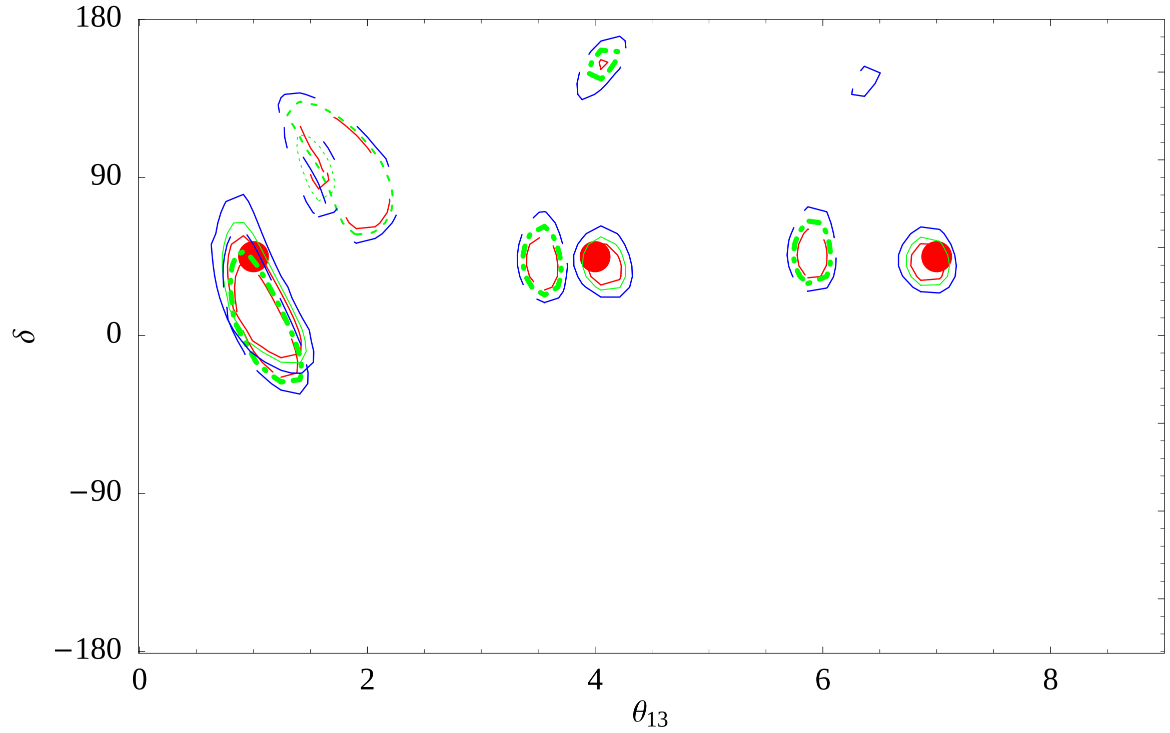
- 40 Kton Magnetized iron detector (MID)
  $L = 2810$ Km (Canary Islands)

  A. Cervera *et al.*,
  Nucl. Instr. Meth. A 451 (2000) 123; NuFact99, Lyon
- 4 Kton Emulsion Cloud Chamber (ECC)
  $L = 732$ Km (Gran Sasso) or $L = 2810$ Km
  D. Autiero *et al.*, hep-ph/0305185; NuFact03, New York

If not possible, we must start thinking to something similar. J. Burguet-Castell *et al.*, hep-ph/0312068

The high-γ Beta Beam

A fifth of the statistics at $\gamma_{^{18}Ne} = 2500, \gamma_{^6He} = 1500$:



$\bar{\theta}_{13} = 1°, 4°, 7°$ $\bar{\delta} = 45°$

$L_{golden} = 2810$ Km, $L_{silver} = 732$ Km

Conclusions

It is crucial to combine experiments and neutrino sources with different L/E to solve the severe parameter degeneracy that obstacles a clean measurement of (θ_{13}, δ).

The Neutrino Factory with three detectors
(a Megaton WC, a magnetized iron detector and an ECC) can do the job for $\theta_{13} \geq 1^\circ$.
It also measures the sign of Δm^2_{atm} and the θ_{23}-octant.
This scenario need update!

A setup including a BetaBeam is, in my opinion, the most interesting option in between the approved SuperBeam Phase-I and, possibly, a Neutrino Factory.

Conclusions, 2

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- High-γ BetaBeam is the only alternative to Neutrino Factory. Technically possible?