The attack of the Clones

A trilogy [a]

[a] J. Burguet-Castell *et al.*, hep-ph/0103258
H. Minakata and H. Nunokawa, hep-ph/0108085
V. Barger *et al.*, hep-ph/0112119

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Now, it is time to join our forces!
Time for the Fall of the Clones.

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

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

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

NuFact03: The Fate of the Clones

Solving degeneracies

A. Donini

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In collaboration with:

J. Burguet-Castell, A. Cervera, M.B. Gavela

J.J. Gomez-Cadenas, P. Hernandez, D. Meloni,

O. Mena, P. Migliozzi, R. Petti,

S. Rigolin, F. Terranova

The PMNS matrix

- $|\Delta m^2_{23}| = (2.6 \pm 0.4) \cdot 10^{-3}$ eV^2
- $\Delta m^2_{12} = (7.3 \pm 0.8) \cdot 10^{-5}$ eV^2 (LMA-I, best)
  $\Delta m^2_{12} = (15.4 \pm 0.8) \cdot 10^{-5}$ eV^2 (LMA-II)

- $\sin^2(2\theta_{23}) = (1.0^{+0.00}_{-0.05})$
- $\sin^2(2\theta_{12}) = (0.315 \pm 0.035)$
- $\sin^2(2\theta_{13}) \leq 0.07$

- The sign of Δm^2_{23}
- The θ_{23}-octant
- Is θ_{13} different from zero?
- Is δ different from zero?

The Golden channel

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

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

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

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 Coefficients

For the golden channel we have:

$$\begin{cases} X_\pm &= \Delta^2_{atm} \times f^\pm_X(\theta_{23}, A, L) \\ Y_\pm &= \Delta_{sun} \times \Delta_{atm} \times f^\pm_Y(\theta_{12}, \theta_{23}, A, L) \\ Z &= \Delta^2_{sun} \times f_Z(\theta_{12}, \theta_{23}, A, L) \end{cases}$$

For the silver channel we have:

$$\begin{cases} X^\tau_\pm &= (c^2_{23}/s^2_{23}) X_\pm \\ Y^\tau_\pm &= Y_\pm \\ Z^\tau &= (s^2_{23}/c^2_{23}) Z \end{cases}$$

($+$ neutrinos, $-$ antineutrinos)
Notice: X, Z interchange $\theta_{23} \to \pi/2 - \theta_{23}$.

Curves in the (θ_{13}, δ) plane

The number of wrong-sign muons is:

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

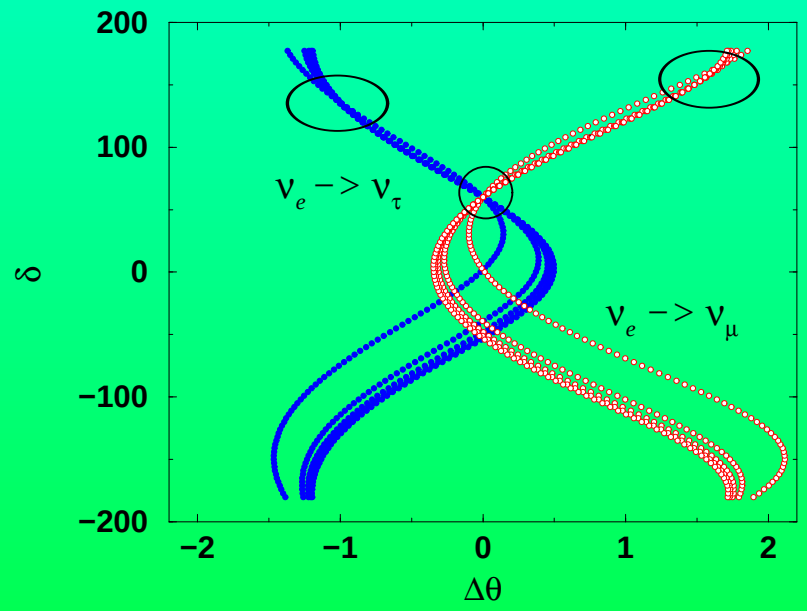
$$N^i_{\mu^-}(\bar{\theta}_{13}, \bar{\delta}) = BR\,(\tau \to \mu) \times \left\{ dN_{\mu^-} \otimes \sigma_{\nu_\tau} \otimes P^+_{e\tau}(\bar{\theta}_{13}, \bar{\delta}) \otimes \Phi_{\nu_e} \right\}_{E_i}^{E_i + \Delta E}$$

with i a given energy bin.
We draw curves in the (θ_{13}, δ) plane:

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

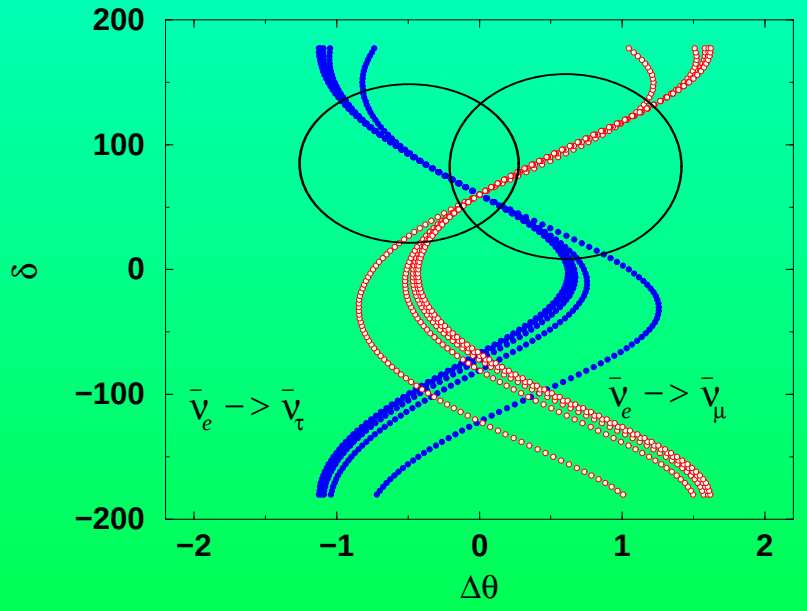
The intrinsic clones

$L = 732$ Km



Neutrinos

$L = 732$ Km



Antineutrinos

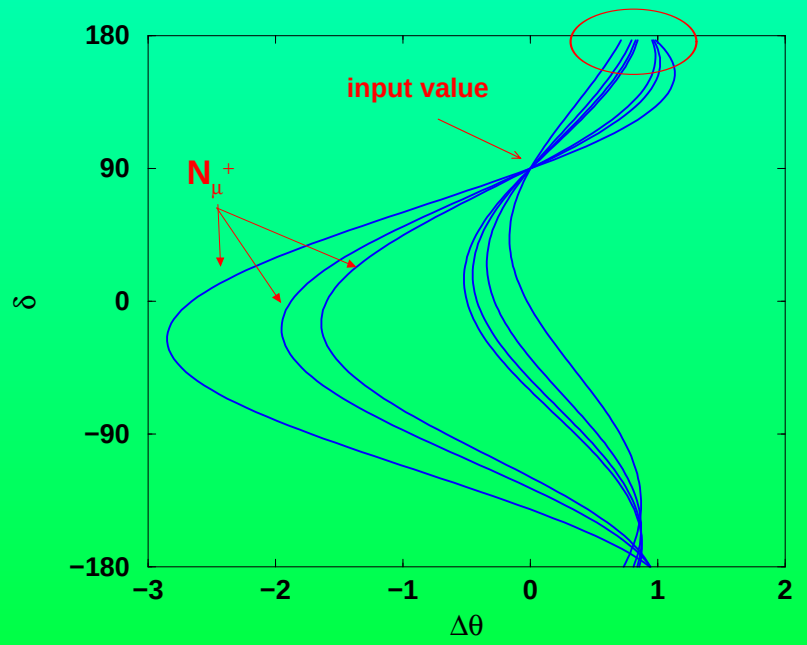
$$\begin{cases} \bar{\theta}_{13} = 5^\circ \\ \bar{\delta} = 90^\circ \end{cases}$$

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

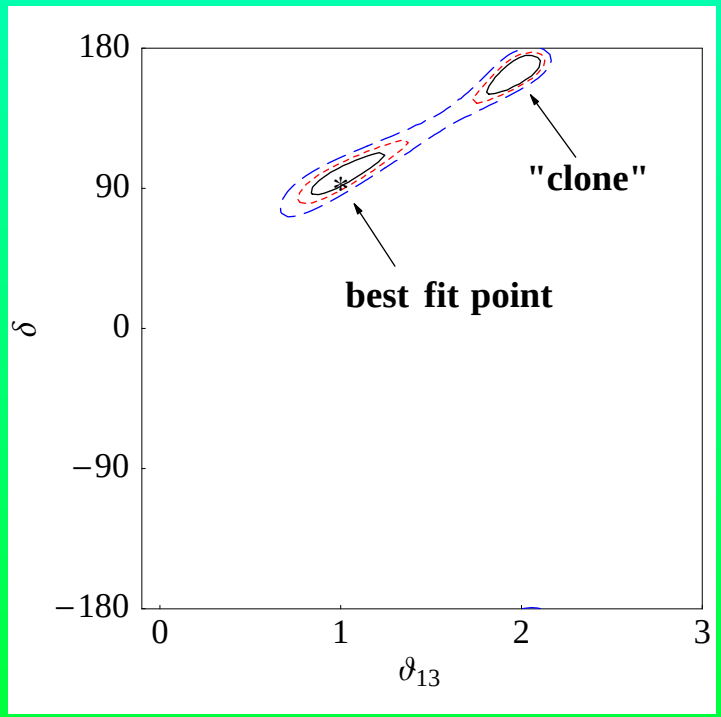
Golden muons at $L = 2810$ Km

Ten years of data taking: two polarities

(μ^+ and μ^- in the storage ring)



$\Rightarrow$



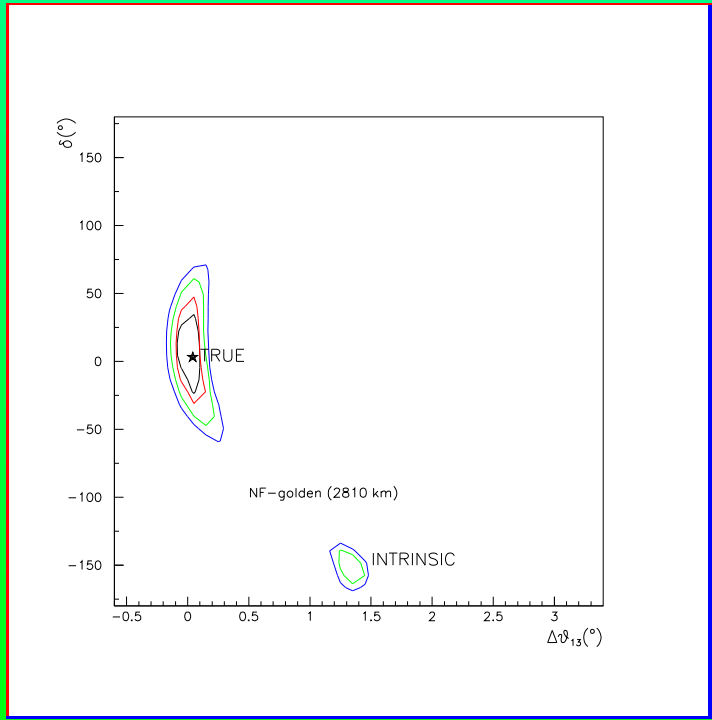
Input parameters: $\bar{\theta}_{13} = 1°, \bar{\delta} = 90°$

The other clones

As a first step:

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

The intrinsic clone



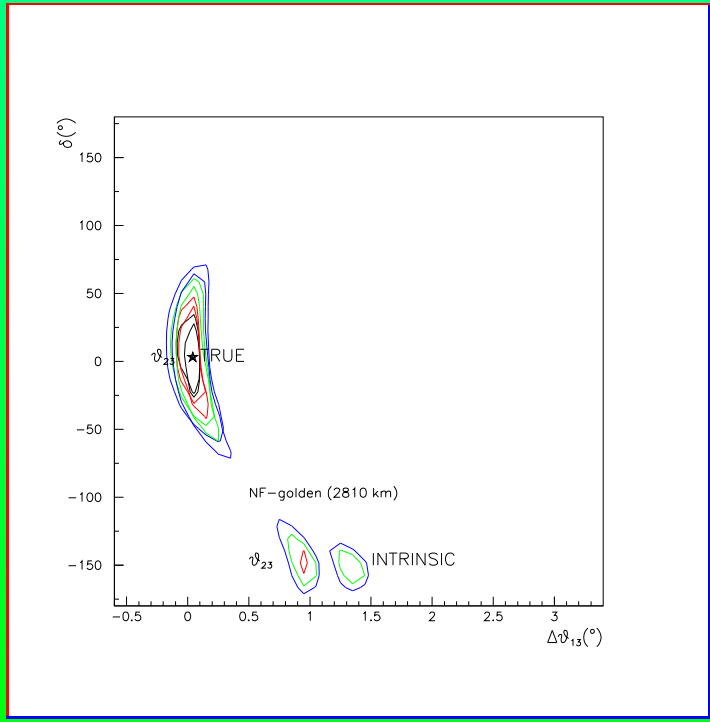
The other clones

As a first step:

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

One more ambiguity:

- the θ_{23}-octant



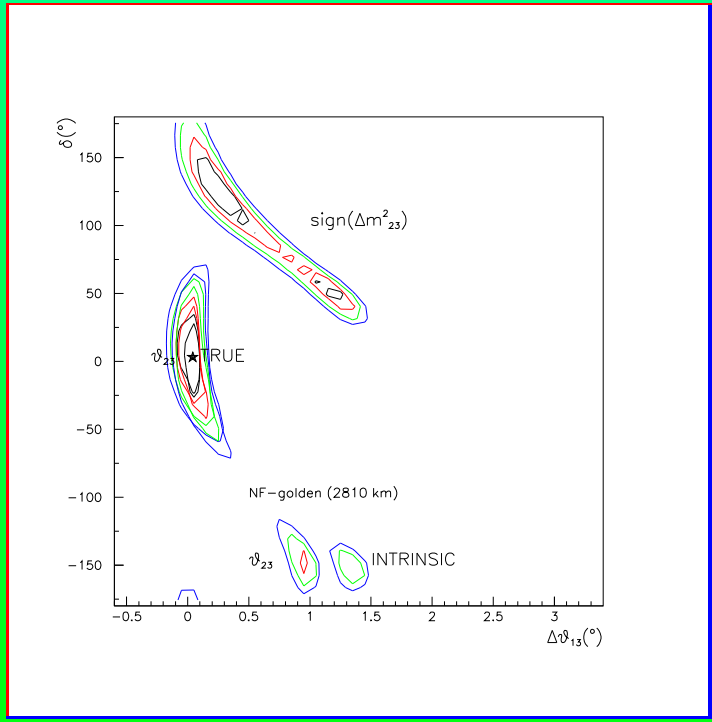
The other clones

As a first step:

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

Two more ambiguities:

- the θ_{23}-octant
- the sign of Δ_{atm}



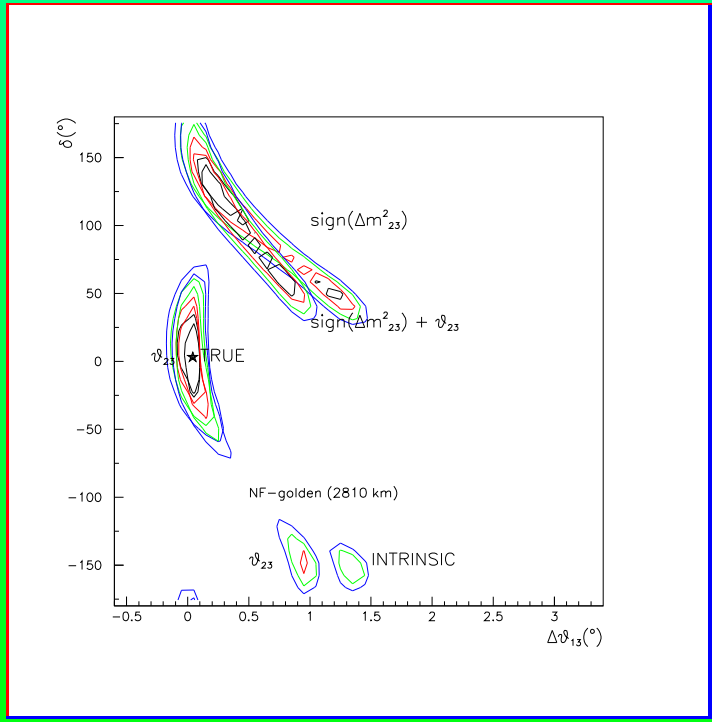
The other clones

As a first step:

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

Three more ambiguities:

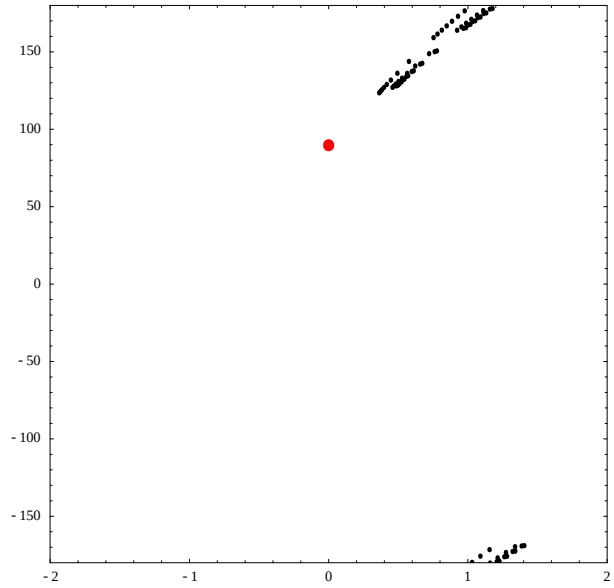
- the θ_{23}-octant
- the sign of Δ_{atm}
- the combination of the two



Location of the clones

Where are the clones?

- Intrinsics

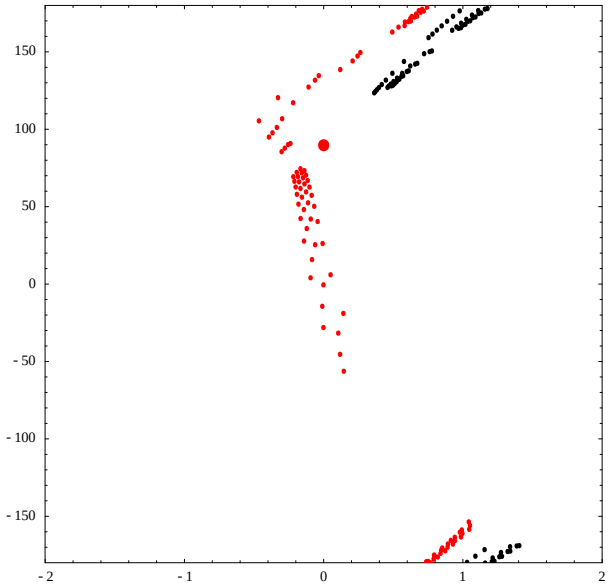


$$\bar{\delta} = 90^\circ$$
$$\bar{\theta}_{13} \in [0.01^\circ, 10^\circ]$$

Location of the clones

Where are the clones?

- Intrinsics
- θ_{23}-octants

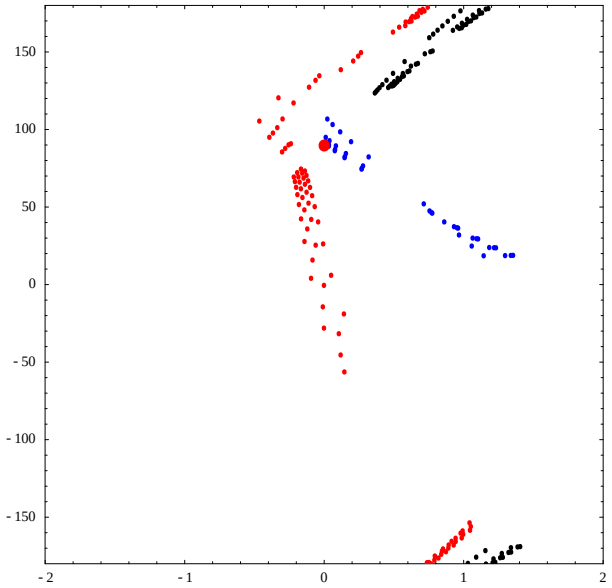


$$\bar{\delta} = 90^\circ$$
$$\bar{\theta}_{13} \in [0.01^\circ, 10^\circ]$$

Location of the clones

Where are the clones?

- Intrinsics
- θ_{23}-octants
- Sign of Δm^2_{atm}

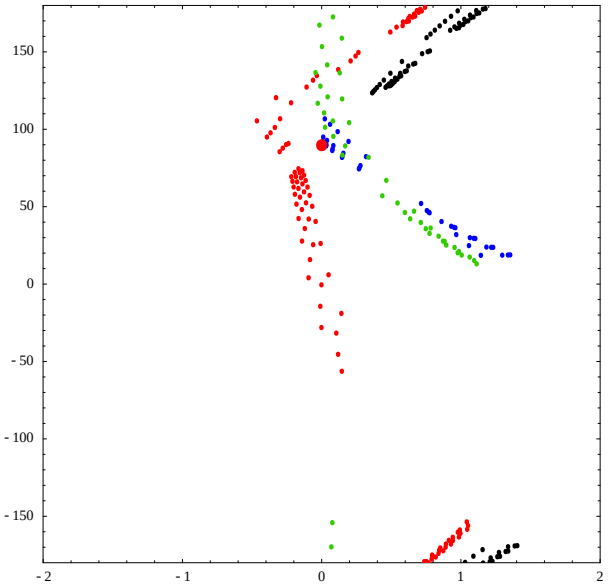


$$\bar{\delta} = 90^\circ$$
$$\bar{\theta}_{13} \in [0.01^\circ, 10^\circ]$$

Location of the clones

Where are the clones?

- Intrinsics
- θ_{23}-octants
- Sign of Δm^2_{atm}
- θ_{23}-octants and Sign of Δm^2_{atm}

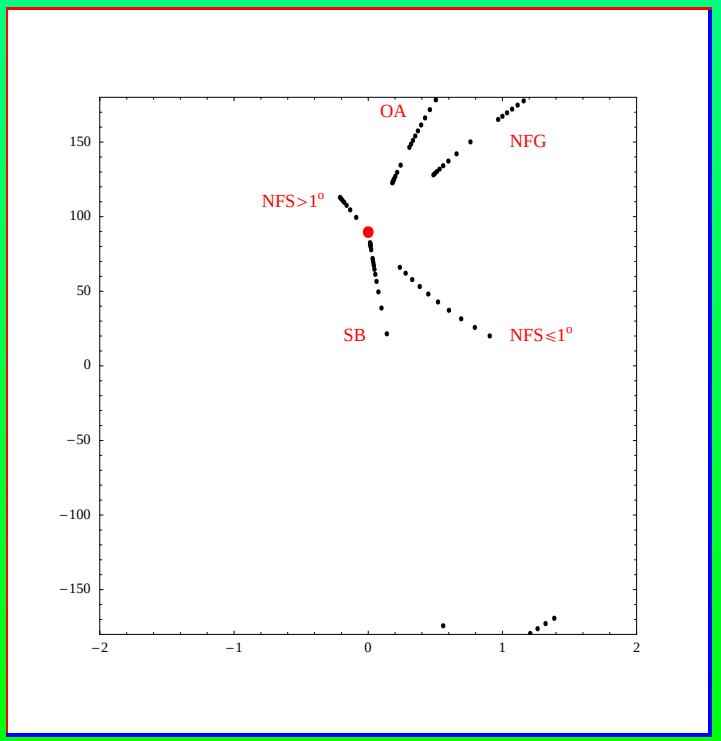


$$\bar{\delta} = 90^\circ$$
$$\bar{\theta}_{13} \in [0.01^\circ, 10^\circ]$$

The understanding of the location of the clones, as a function of

- the flux and the beam characteristics
- the input parameters $(\bar{\theta}_{13}, \bar{\delta})$

allows the optimization of a SETUP that solves all the degeneracies.



The generic Neutrino Factory design includes:

- SuperBeam facility
- two μ-decay tunnels

The Detectors Setup

50 GeV Neutrino Factory located at CERN
Three detectors of different design:

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

  A. Cervera *et al.*,

  Nucl. Instr. Meth. A 451 (2000) 123; NuFact99, Lyon
- 400 Kton Water Cherenkov (WC)
  $L = 130$ Km (Frejus)

  A. Blondel *et al.*,

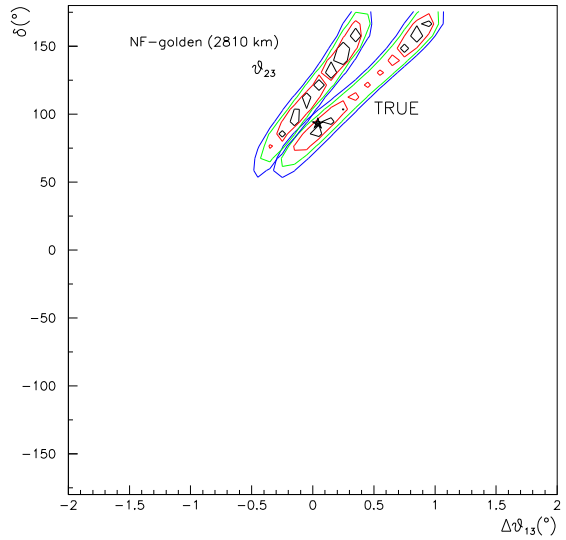
  Nucl. Instr. Meth. A 503 (2001) 173; NuFact01, Tsukuba
- 4 Kton Emulsion Cloud Chamber (ECC)
  $L = 732$ Km (Gran Sasso) or $L = 2810$ Km

  D. Autiero *et al.*, hep-ph/0305185; NuFact03, New York

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



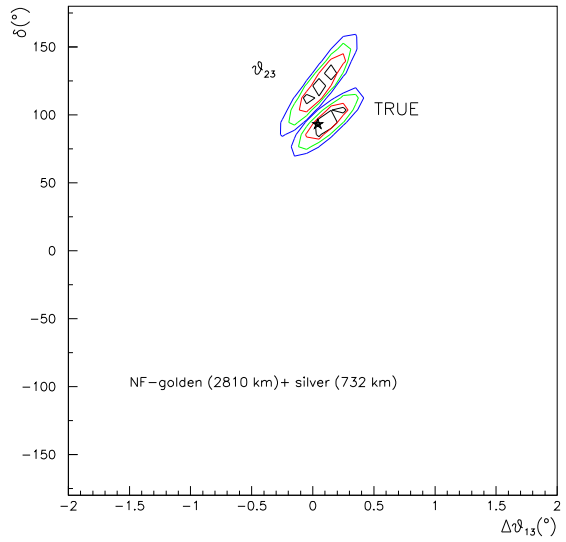
$\bar{\theta}_{13} = 2^\circ \; \bar{\delta} = 90^\circ$

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



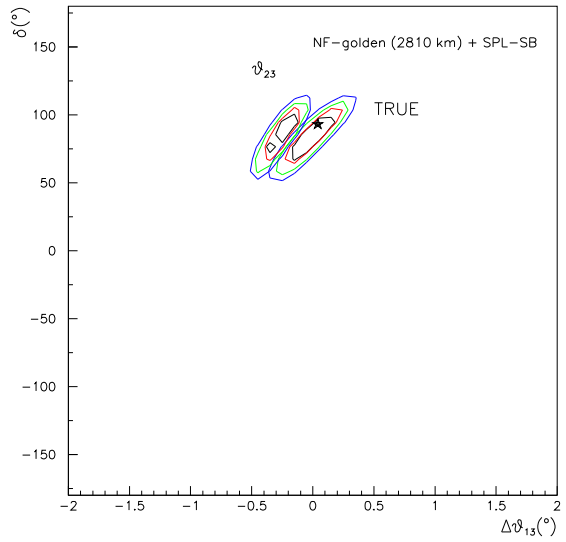
$\bar{\theta}_{13} = 2^\circ \; \bar{\delta} = 90^\circ$

Two detectors

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

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

- 40 Kton MID
- 400 Kton WC



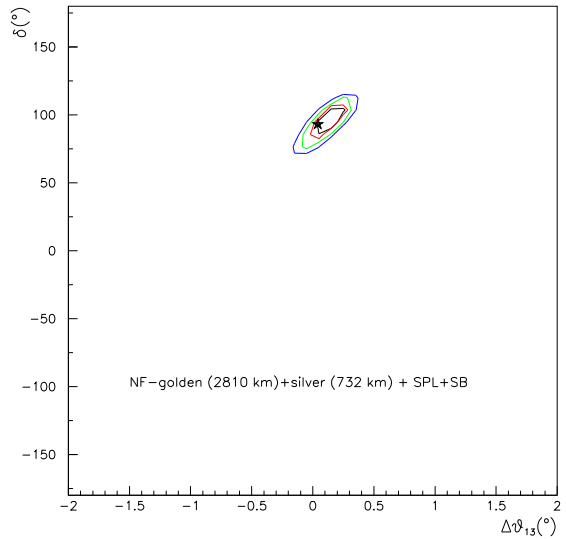
$\bar{\theta}_{13} = 2^\circ \; \bar{\delta} = 90^\circ$

The Three Detectors

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

.... Halleluja....

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



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

Sensitivity limits

Statement:

All degeneracies solved for $\theta_{13} \geq 1^\circ$

$(\sin^2 2\theta_{13} \geq 0.001)$

However, three comments are in order:

- 4 Kton ECC: statistical limit at $\sim 1^\circ$
  (P. Migliozzi's talk and hep-ph/0305185)
- 40 Kton MID: effect of systematics?
  (P. Migliozzi's talk and hep-ph/0305185)
- 400 Kton WC: can we reduce its mass?
  how this affects our results?

A conservative statement:

All degeneracies solved for $\theta_{13} > 1^\circ$

Conclusions

(θ_{13}, δ) correlations and (approximate) discrete parities in the sign of Δ_{atm} and in the θ_{23}-octant induce EIGHT SOLUTIONS at a single experiment.

The generic Neutrino Factory setup consists of a SuperBeam facility and of (at least) two μ-decay channels. The combination of three detectors of different design running at the same time SOLVES all the DEGENERACIES.

$\theta_{13} > 1^\circ$: the physical δ is reconstructed, for any δ.
$\theta_{13} \leq 1^\circ$: further studies are needed. In particular,

- ▷ Systematics of the Golden Channel MID
- ▷ Sensitivity of the Silver Channel ECC