The Approaching future of Leptonic Mixing

El jardín de los caminos que se bifurcan

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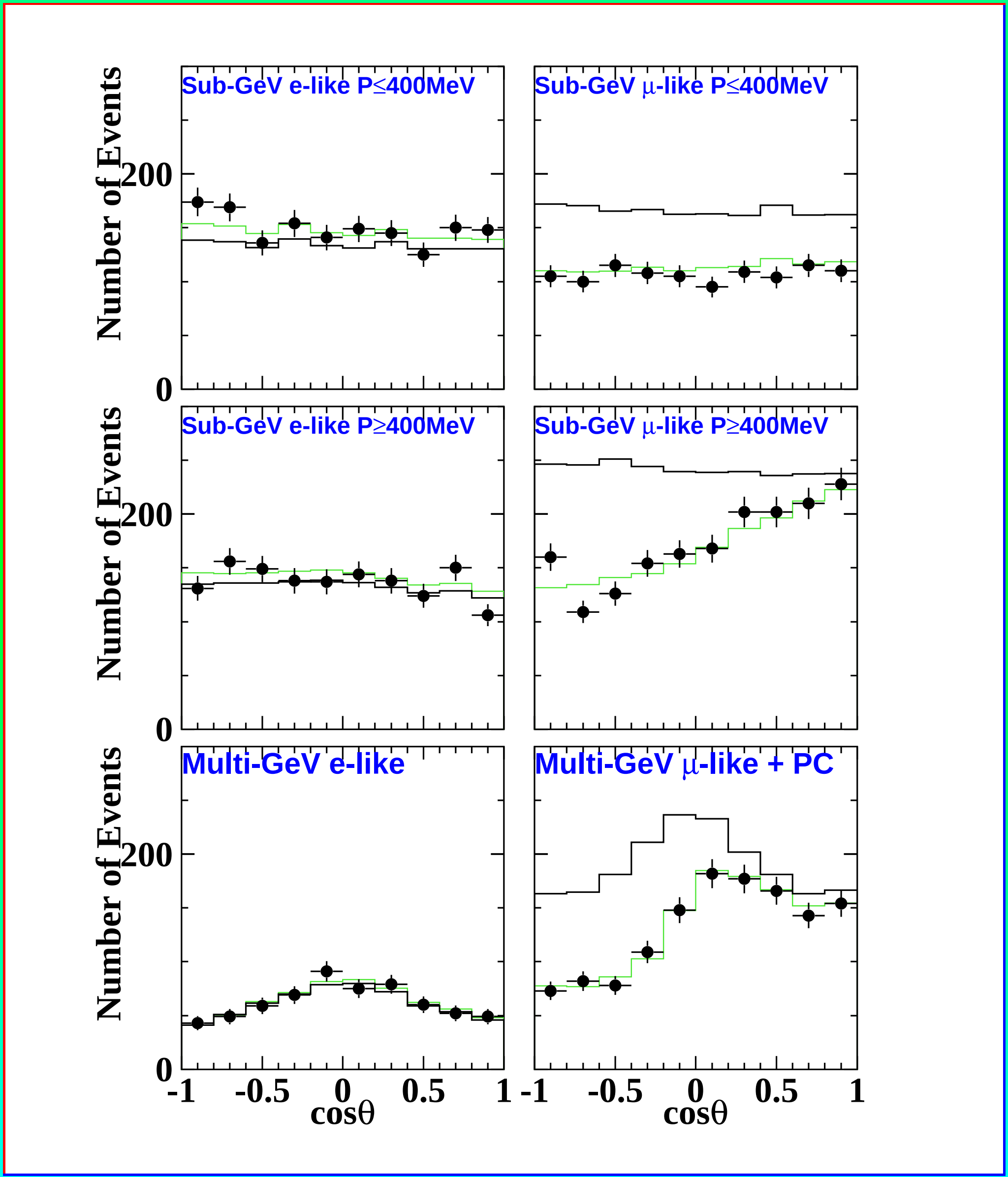
The SuperK atmospheric data



1998:
First strong evidence
of ν_μ oscillations.

Leptonic flavour mixing

The **Pontecorvo-Maki-Nakagawa-Sakata** matrix:

$$\begin{pmatrix} \text{FlavourBasis} \\ |\nu_\alpha\rangle \end{pmatrix} = \sum_i U^{\alpha\, i}_{\text{PMNS}} \times \begin{pmatrix} \text{MassBasis} \\ |\nu_i\rangle \end{pmatrix}$$

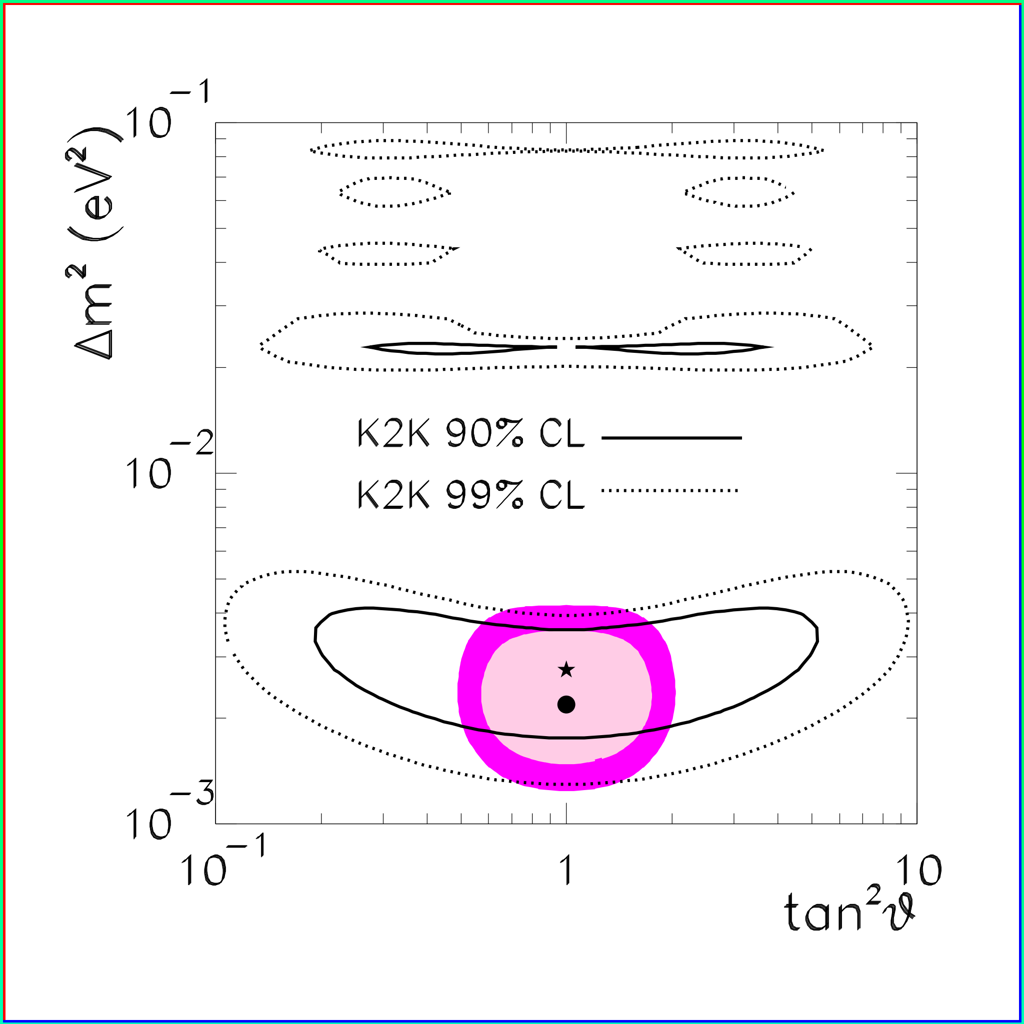
and its space-evolution:

$$i\,\frac{d}{dx}\,|\nu_\alpha\rangle = \sum_\beta \left(U\ \left[\frac{\Delta m^2}{2E_\nu}\right] U^\dagger + [A] \right)_{\alpha\beta} |\nu_\beta\rangle$$

$$\left[\frac{\Delta m^2}{2E_\nu}\right] = \frac{1}{2E_\nu}\text{diag}(0, \Delta m^2_{21}, \Delta m^2_{31})$$

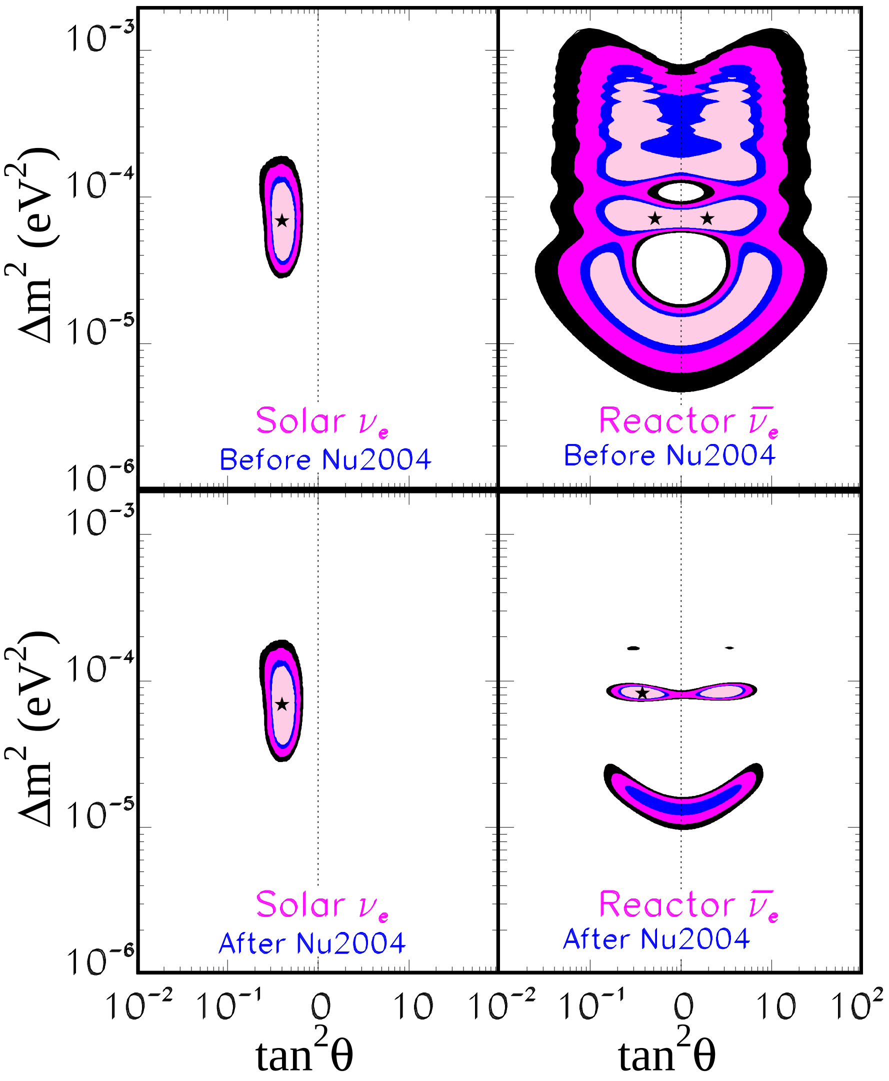
$$[A] = \text{diag}(\sqrt{2}G_F N_e, 0, 0)$$

The atmospheric sector



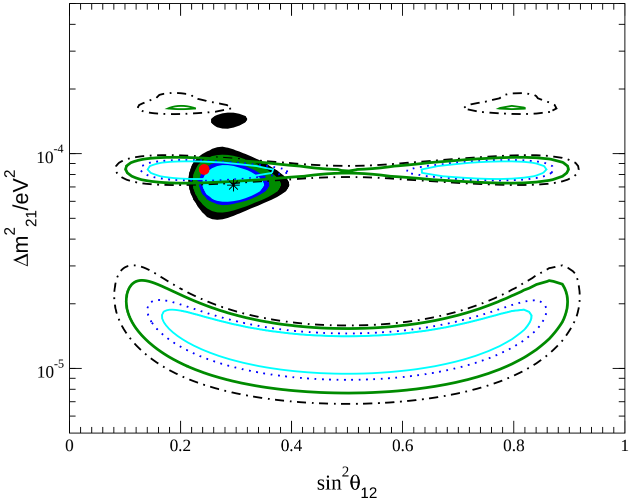
Atmospheric data
plus
K2K
a conventional beam:
$\pi^{\pm} \to \mu^{\pm}\nu_{\mu}(\bar{\nu}_{\mu})$

The solar sector



The solar sector, 2

Solar + KamLand (old)



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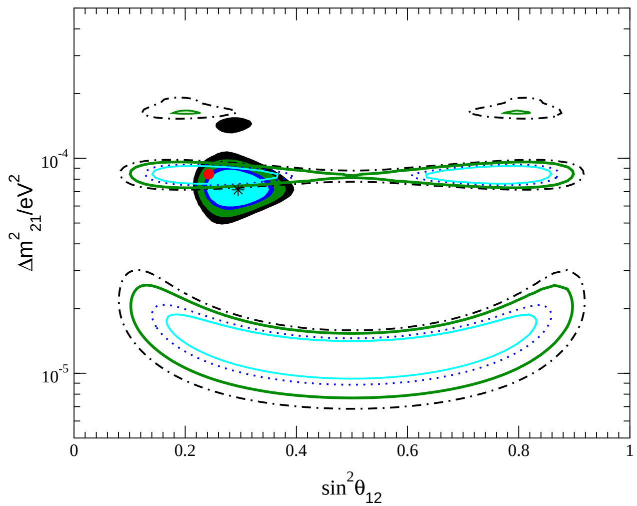
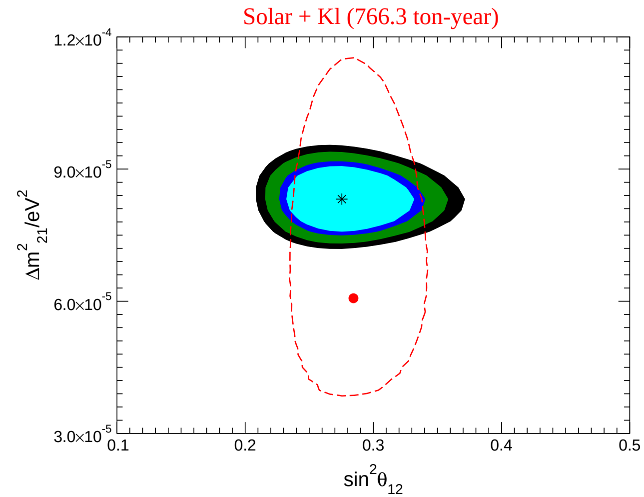
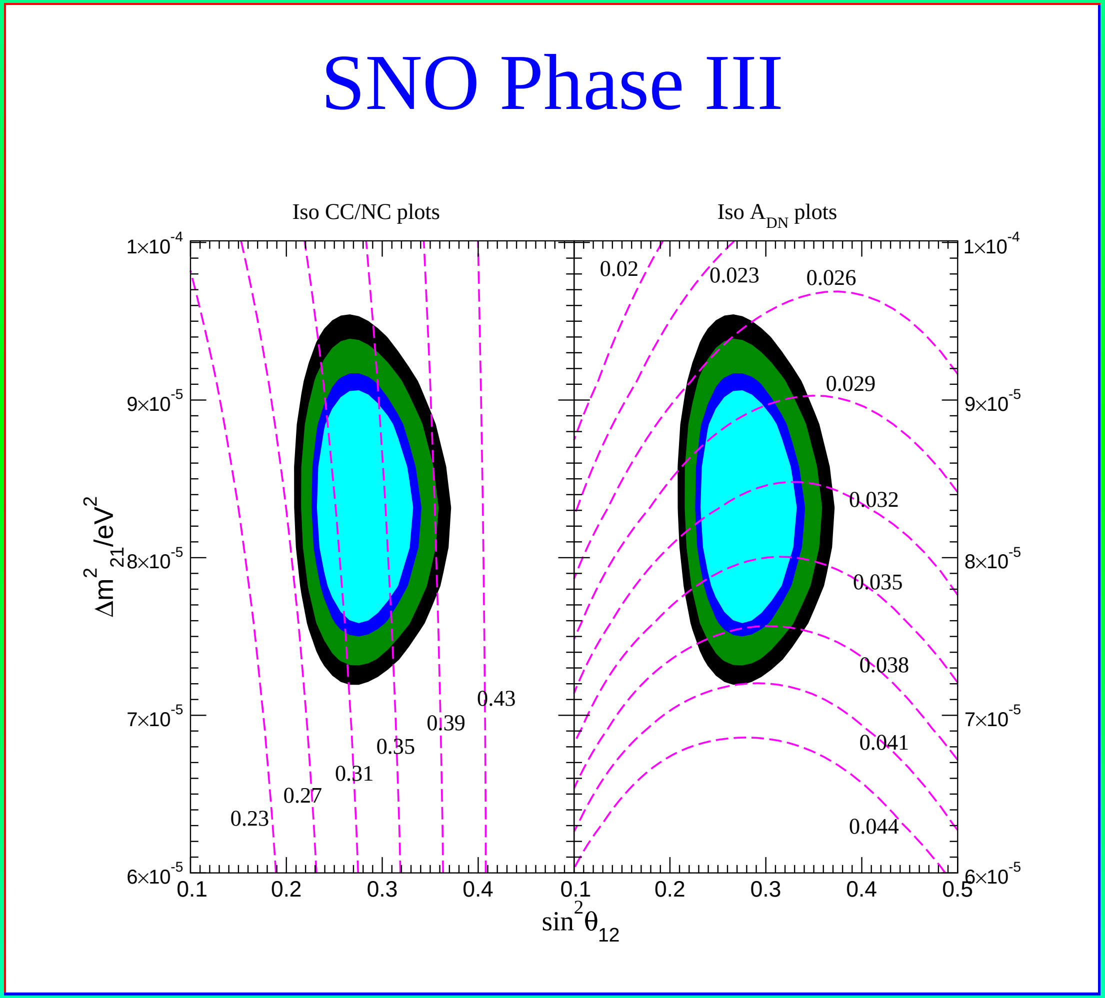


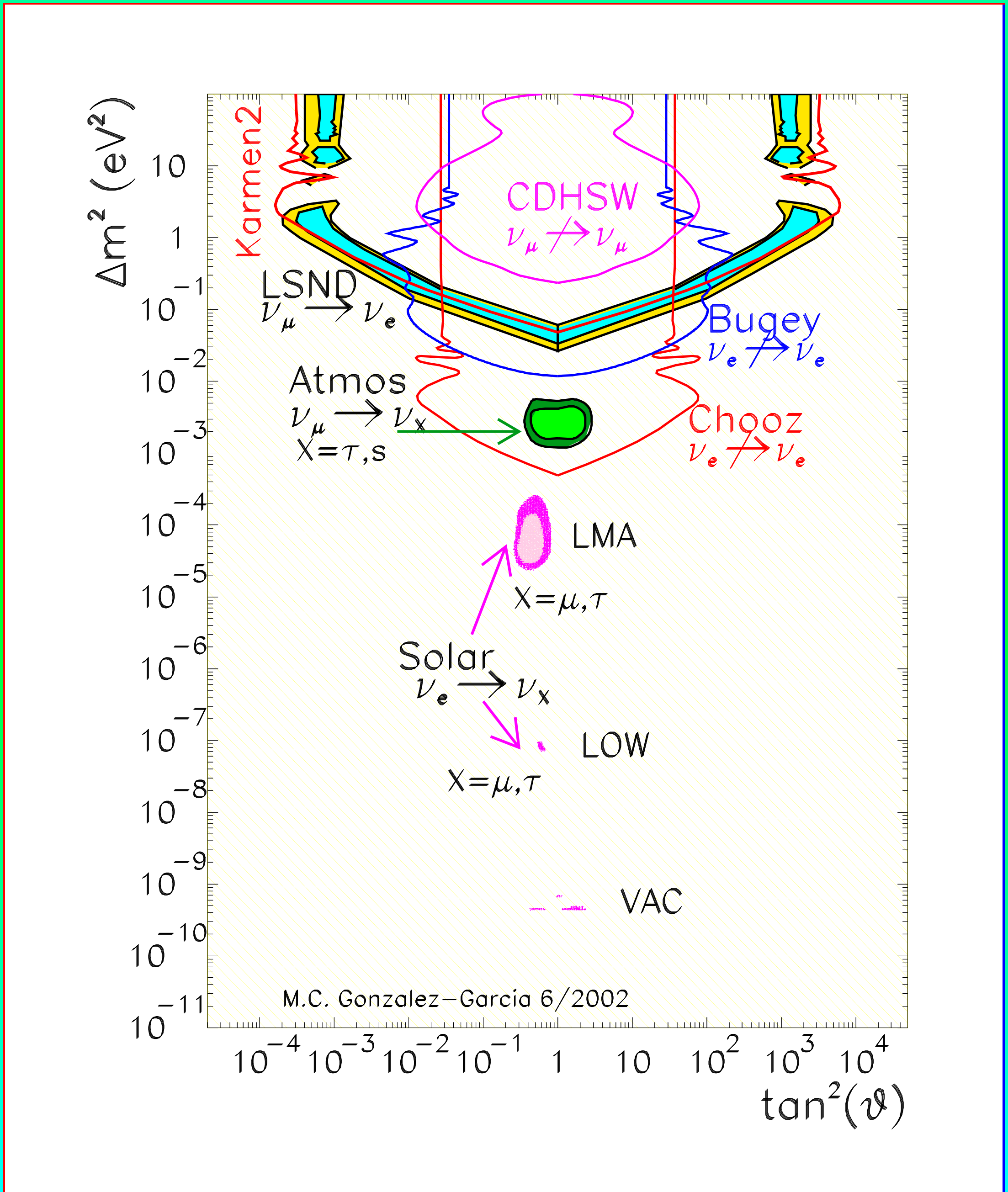
Solar + KamLand (new)



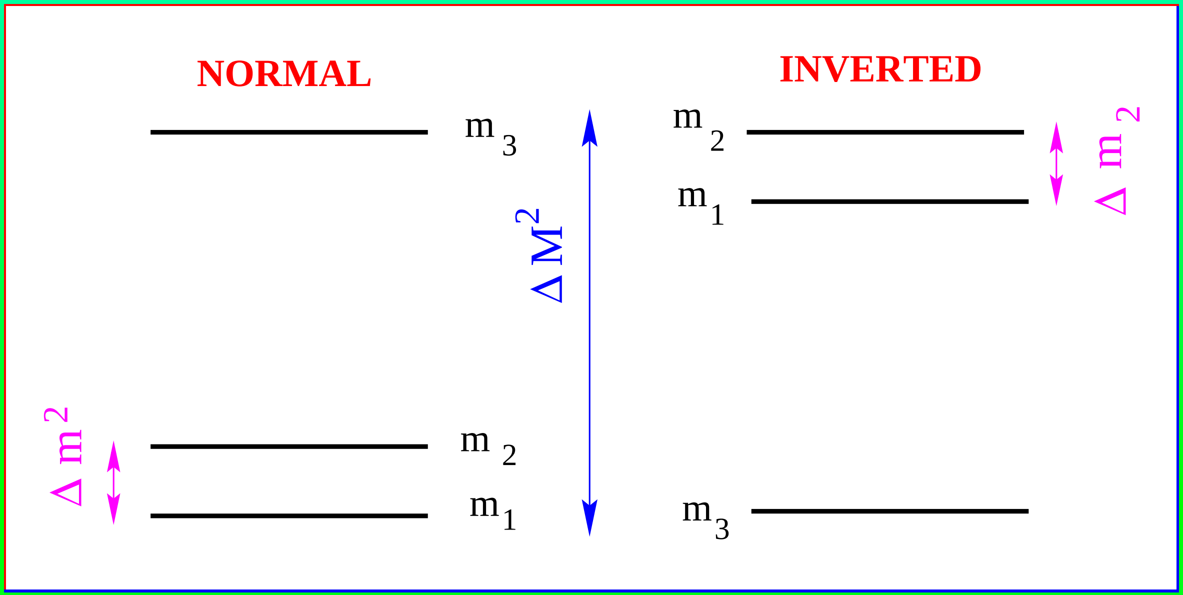
The solar sector, 3



The LSND puzzle



The mass hierarchy



Present data do not distinguish between normal and inverted hierarchy

The PMNS matrix

- $|\Delta m^2_{atm}| = (2.6 \pm 0.4) \cdot 10^{-3}$ 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?

Two more missing pieces

- The absolute neutrino mass:
  tritium decay experiments;
  cosmological bounds (WMAP, PLANCK, ...)
- Majorana or Dirac neutrinos?
  neutrinoless double-β decay experiments;
  plenty of additional phases,
  needed for LEPTOGENESIS.

I will not cover these two items in this talk.

Neutrino sources

- Natural sources:
  - ★ The Sun $\longrightarrow \nu_e$
  - ★ Cosmic rays $\longrightarrow \nu_e, \nu_\mu$
  - ★ Supernovae and relic SNs $\longrightarrow \nu_e, \nu_\mu, \nu_\tau$ (wait for gadolinium SK!)
  - ★ Geoneutrinos !!! $\longrightarrow \nu_e$

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

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
	$\rightarrow 8^\circ$	$\rightarrow 0.08$	$\rightarrow 0.02$
CNGS	5°	0.03	0.008
	$\rightarrow 7^\circ$	$\rightarrow 0.06$	$\rightarrow 0.015$

$P_{\mu\mu} \simeq$

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

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

Foreseeable bounds on θ_{13} (1)

EXP	θ_{13}	$\sin^2(2\theta_{13})$	$\sin^2\theta_{13}$
Global Fit	$11.5°$	0.157	0.041
SBEAMS			
JHF-I	$2.2°$	0.006	0.0015
(T2K)	$\rightarrow 3.3°$	$\rightarrow 0.013$	$\rightarrow 0.0030$
NUMI-OA	$2°$	0.005	0.0010
(NOνA)	$\rightarrow 3.5°$	$\rightarrow 0.015$	$\rightarrow 0.0040$
SPL	$1.2°$	0.003	0.0007
	$\rightarrow 2.9°$	$\rightarrow 0.010$	$\rightarrow 0.0025$

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
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

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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- mixing angles θ_{12}, θ_{23} at 10 %;

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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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- the value of θ_{13}, if large;
- the sign of Δm^2_{23}, if lucky.

Precision measurements of the LEPTONIC MIXING will start with the next-to-next generation man-made sources, the Neutrino Factory and/or the Beta Beam.

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 Coefficients

For the golden channel we have:

$$\begin{cases} X_\pm &= \Delta^2_{atm} \times f_X^\pm(\theta_{23}, A, L, E_\nu) \\ Y_\pm &= \Delta_{sol} \times \Delta_{atm} \times f_Y^\pm(\theta_{12}, \theta_{23}, A, L, E_\nu) \\ Z &= \Delta^2_{sol} \times f_Z(\theta_{12}, \theta_{23}, A, L, E_\nu) \end{cases}$$

($+$ neutrinos, $-$ antineutrinos)

The (θ_{13}, δ) correlation

The number of signal electrons is:

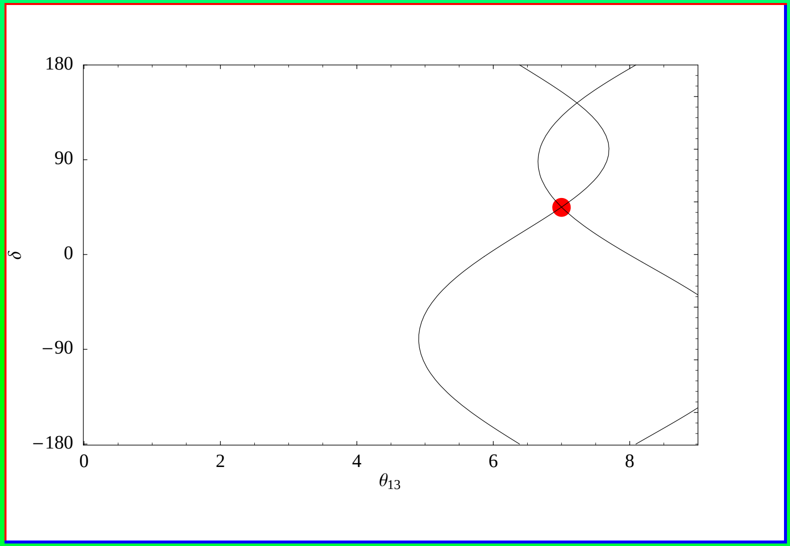
$$N_{e^-}(\bar{\theta}_{13}, \bar{\delta}) = \left\{\epsilon_e \otimes \sigma_{\nu_e} \otimes P^{+}_{\mu e}(\bar{\theta}_{13}, \bar{\delta}) \otimes \Phi_{\nu_\mu}\right\}_{E}^{E+\Delta E}$$

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

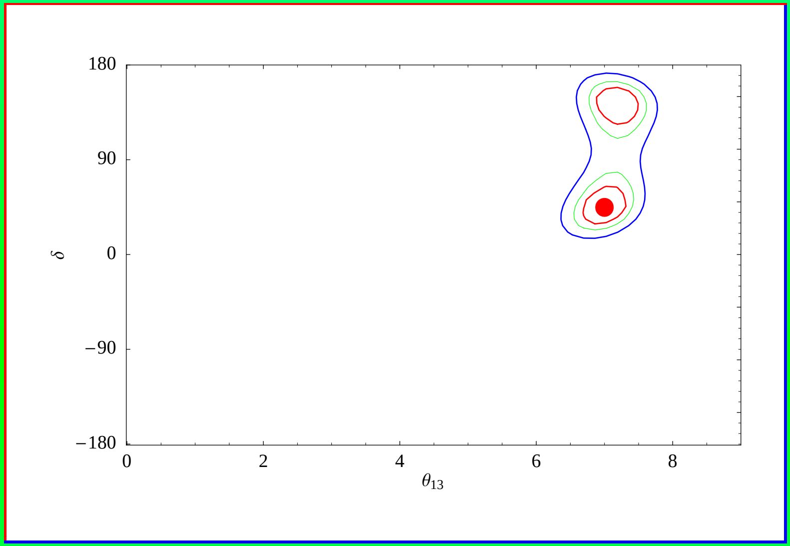
By changing (θ_{13}, δ) accordingly,
curves are drawn in the (θ_{13}, δ) plane.

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

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

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

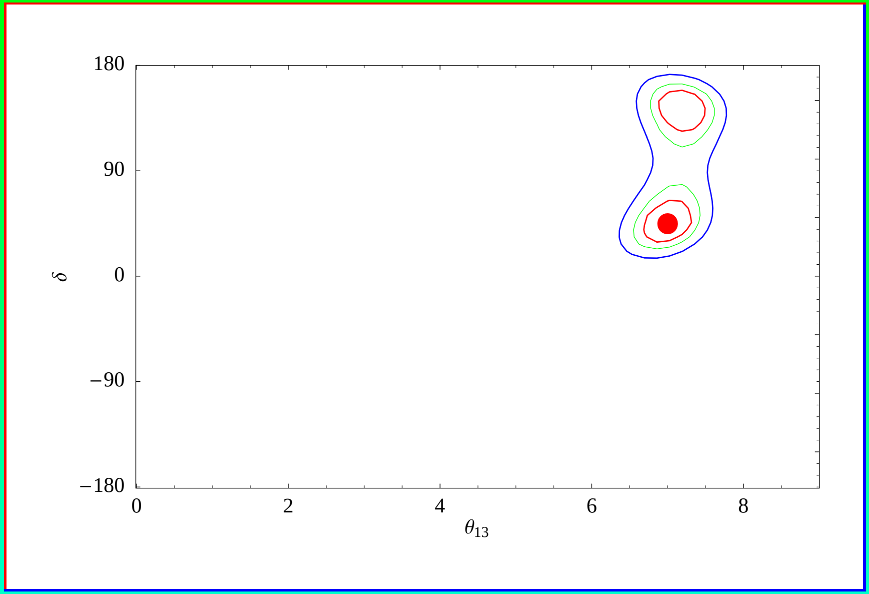
Of other clones

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

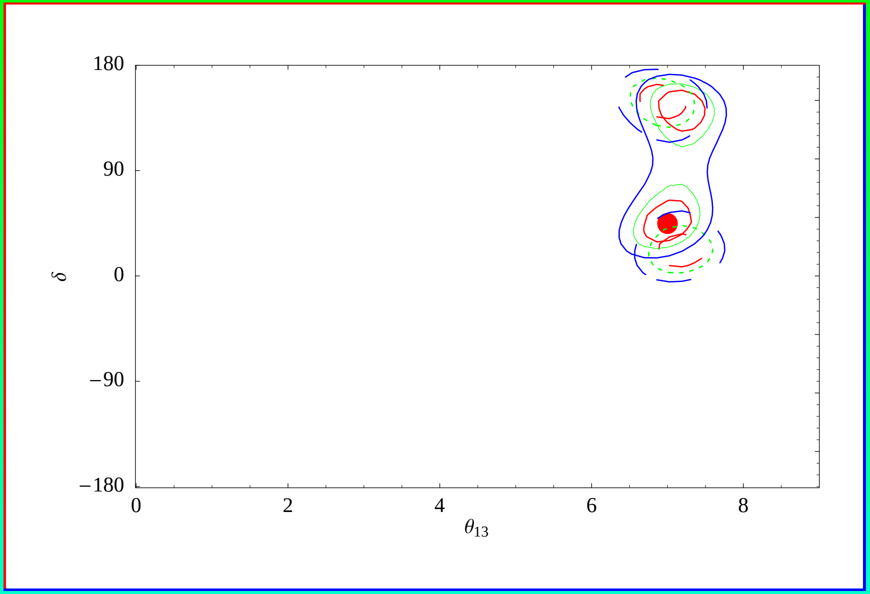
As a third step:

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

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

One more ambiguity:

- ▷ the sign clone



Of other clones

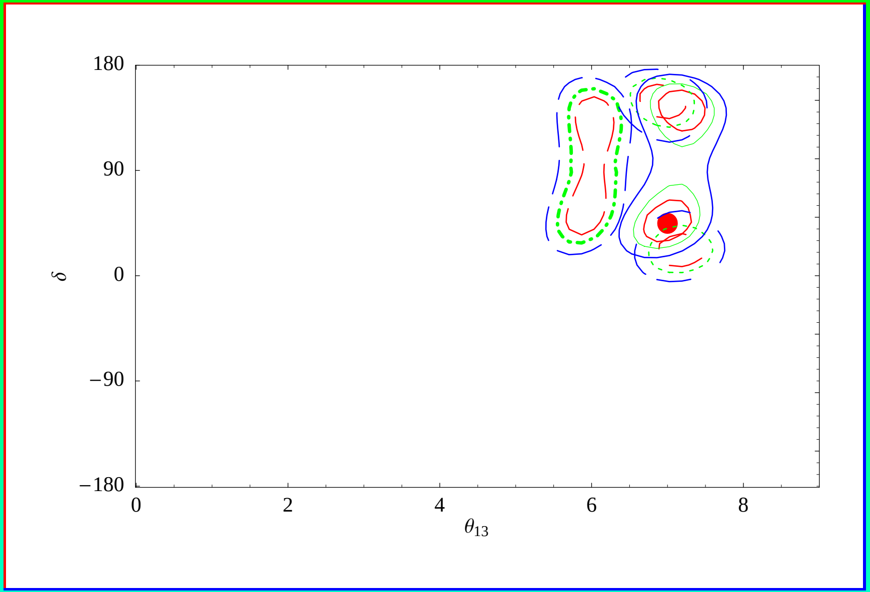
As a second step:

- $\theta_{23} \neq 45^\circ$
- 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

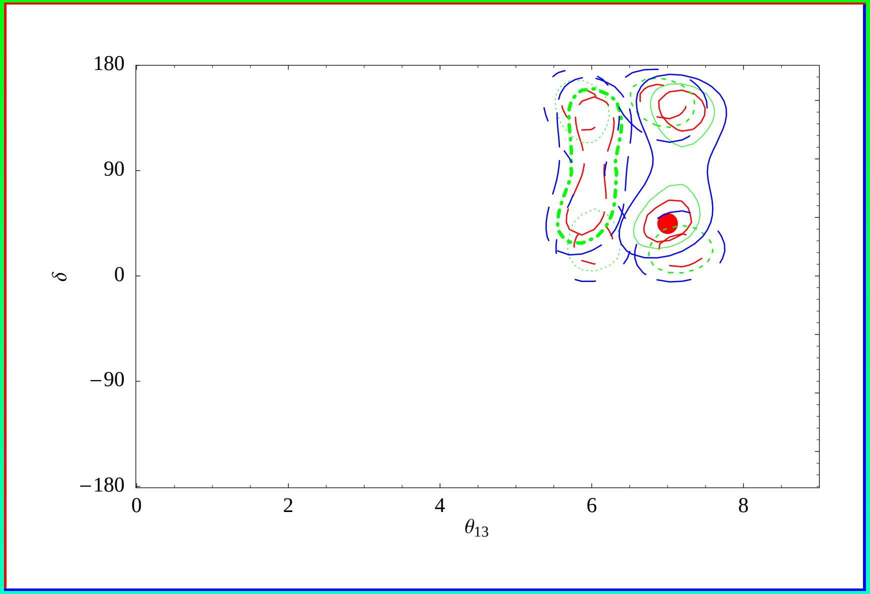
As a fourth step:

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

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

Three more ambiguities:

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



Solving degeneracies

It is possible to compute analytically the location of each clone in the (θ_{13}, δ) plane as a function of

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

A.Donini, D.Meloni and S.Rigolin, hep-ph/0312072

E.g., for the intrinsic clones in vacuum:

$$\sin^2 2\theta_{13} = \sin^2 2\bar{\theta}_{13} + \frac{1}{D^2}\left[1 + 2D\cos\bar{\delta}\sin 2\bar{\theta}_{13}\right]$$

These results can be used, in principle, to design experiments with complementary characteristics to solve the parameter degeneracies.

The understanding of the clones location permits to study a SETUP to solve most of the degeneracies.

Two possible setups:

- ▷ The Neutrino Factory
- ▷ The Beta Beam

Both facilities are multi-sources plants, including:

- one SuperBeam facility
- two μ or heavy ion decay tunnels

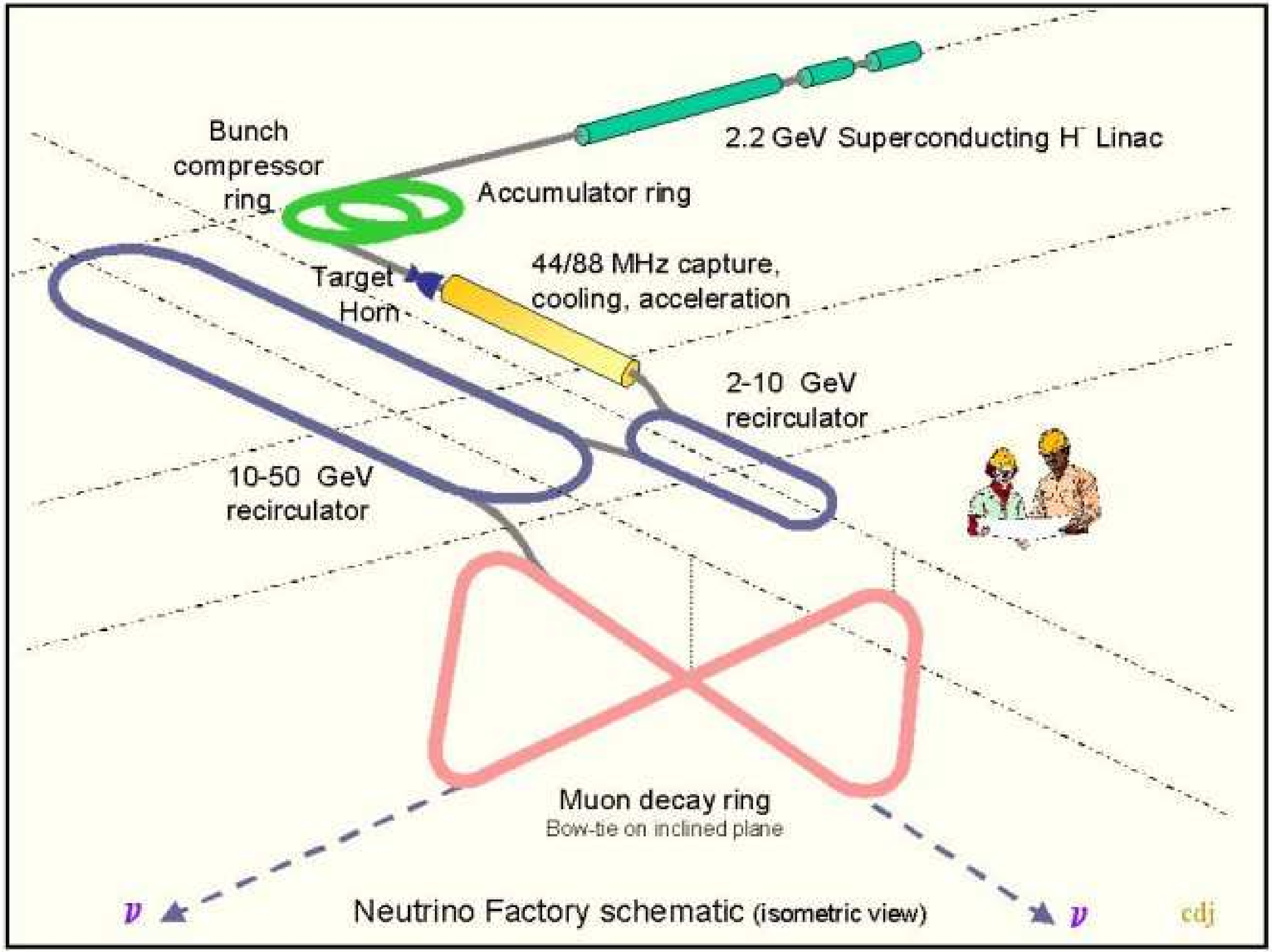
Neutrino Factory setup:

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

BetaBeam setup:

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

The Neutrino Factory at CERN



The Golden channel: ν-factory

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

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

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 Coefficients

For the golden channel we have:

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

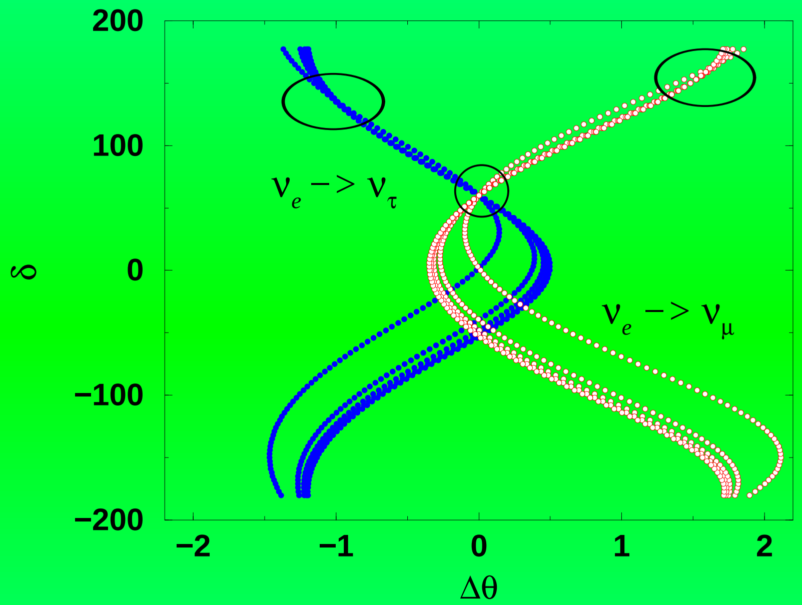
For the silver channel we have:

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

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

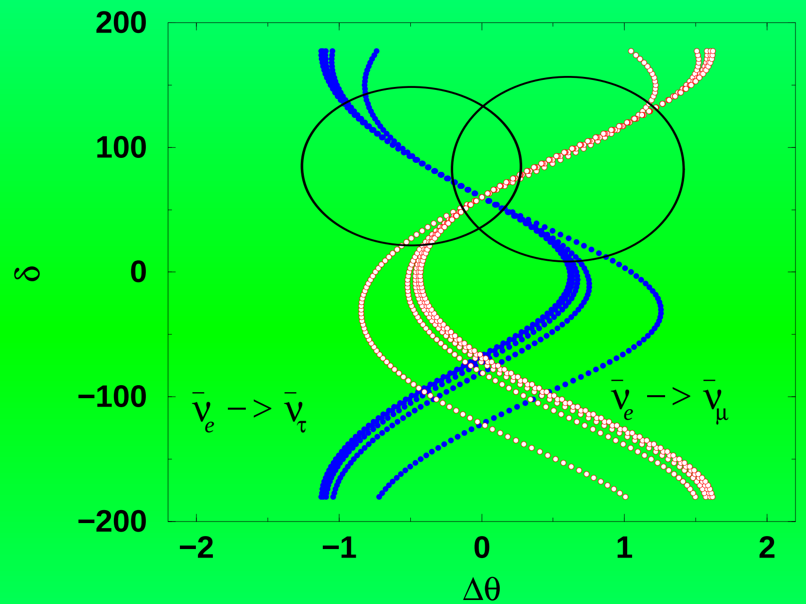
The intrinsic clones

$L = 732$ Km



Neutrinos

$L = 732$ Km



Antineutrinos

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

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

The ν-factory/detectors setup

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

- 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

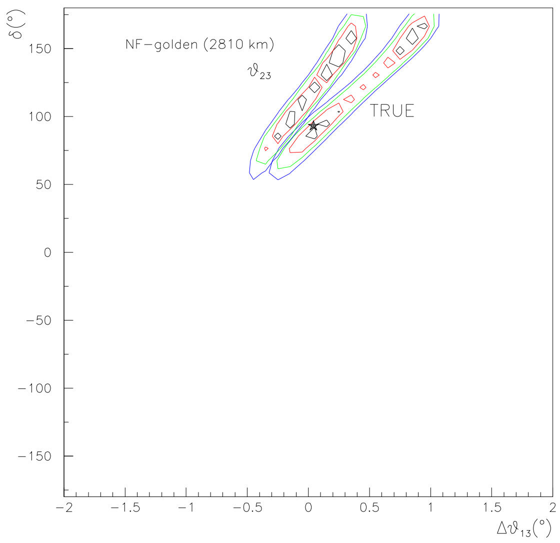
  D. Autiero *et al.*, hep-ph/0305185; NuFact03, New York

One detector

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

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

- 40 Kton MID



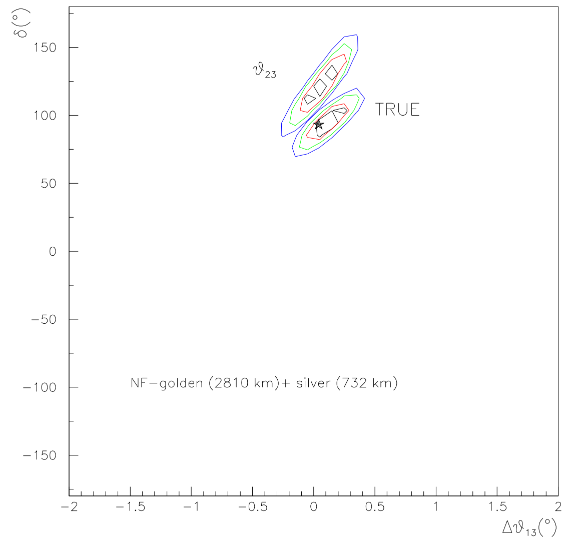
$\bar{\theta}_{13} = 2°$ $\bar{\delta} = 90°$

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



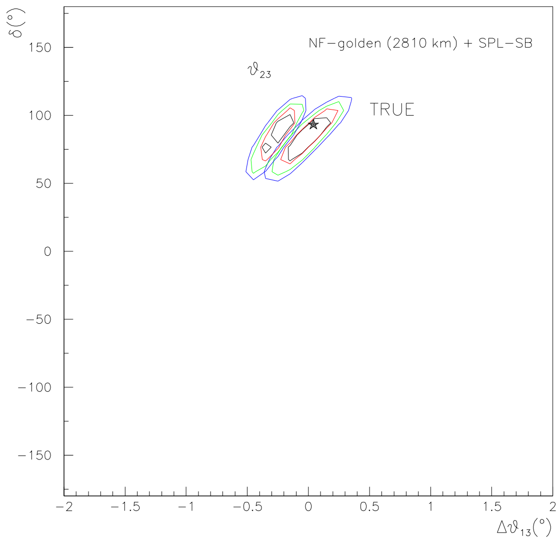
$\bar{\theta}_{13} = 2^\circ \; \bar{\delta} = 90^\circ$

Two detectors

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

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

- 40 Kton MID
- 400 Kton WC



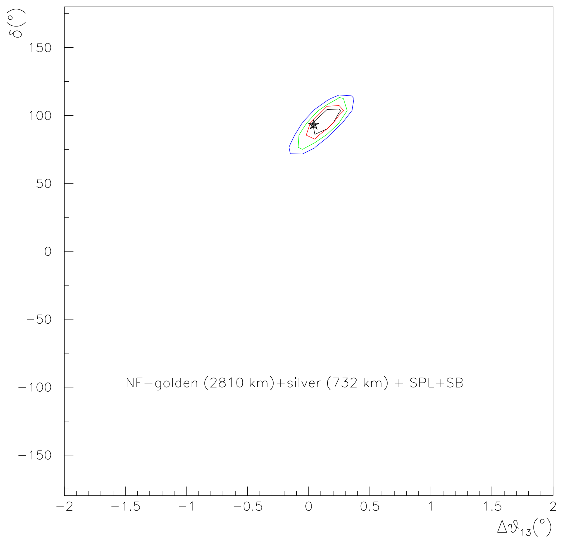
$$\bar{\theta}_{13} = 2° \ \bar{\delta} = 90°$$

The Three Detectors

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

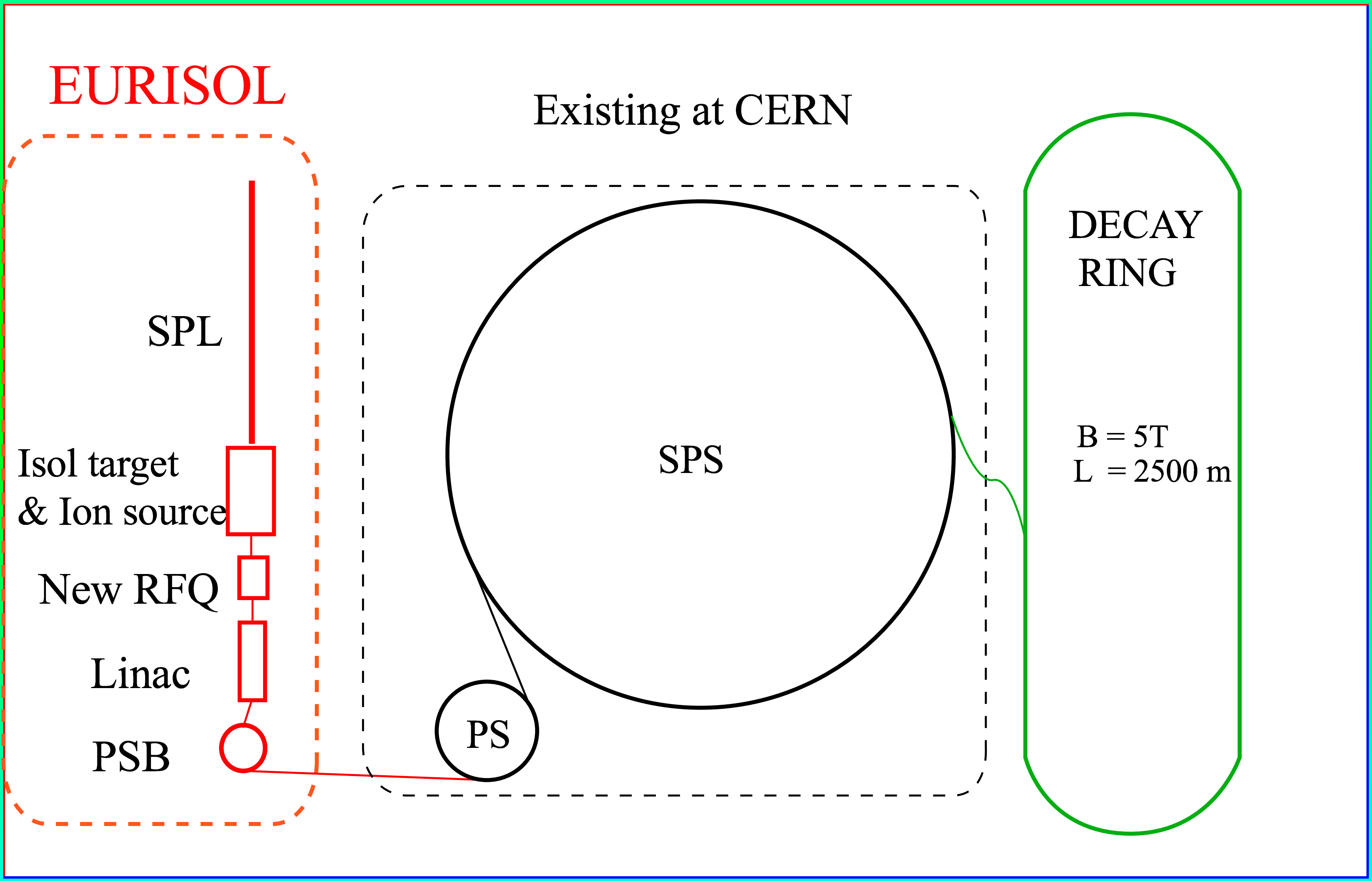
A. Donini, hep-ph/0310014

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



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

The Beta-Beam at CERN



The Golden channel: β-beam

$$\boxed{{}^{18}\mathrm{Ne}} \rightarrow \begin{cases} e^{+} \\ {}^{19}\mathrm{F} \\ \boxed{\nu_e \rightarrow \nu_\mu \rightarrow \mu^{-}} \end{cases} \qquad Signal$$

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 β-beam/detector setup

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.

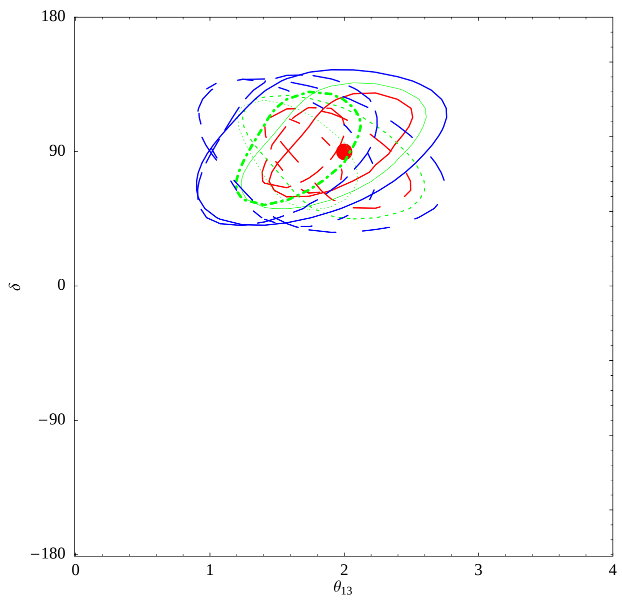
The high-γ option must be considered seriously:
J. Burguet-Castell *et al.*, hep-ph/0312068

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

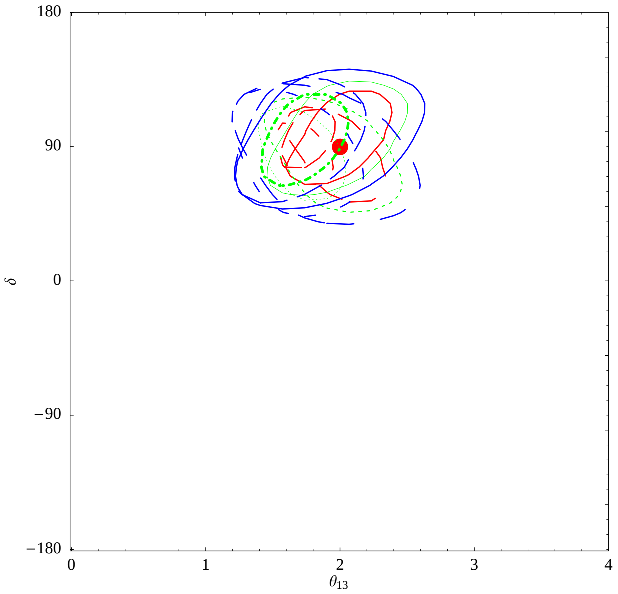


$\bar{\theta}_{13} = 2^\circ \ \bar{\delta} = 90^\circ$

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

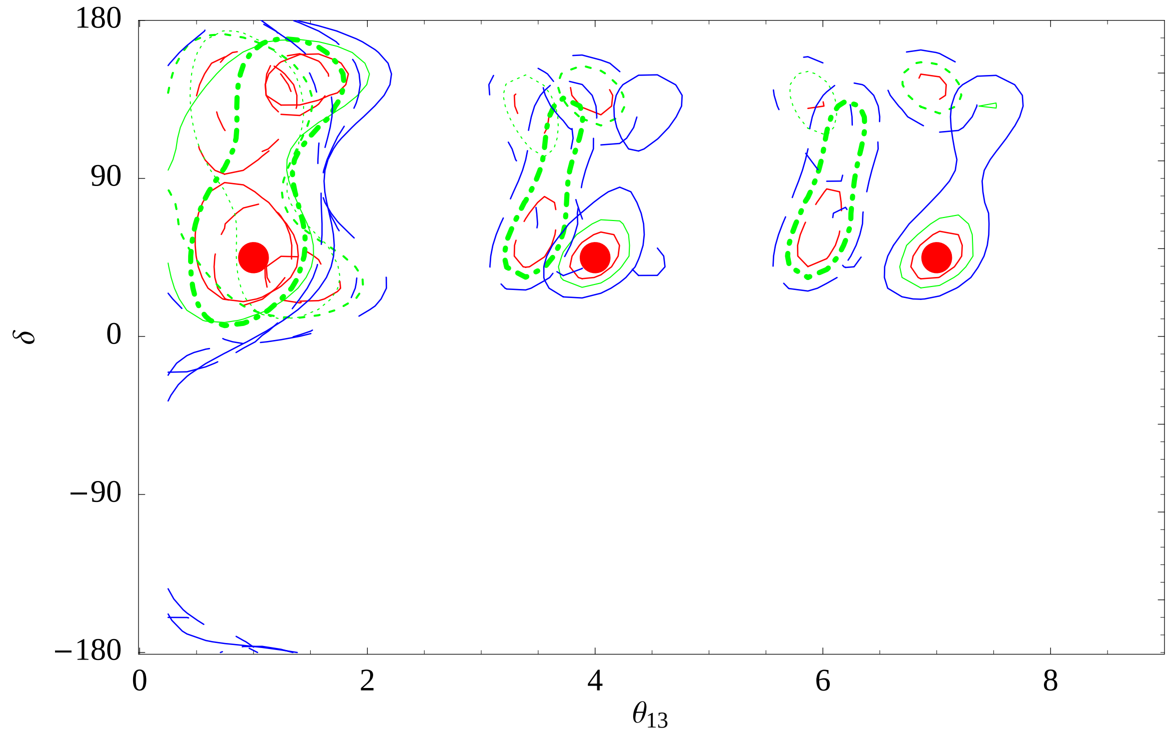


$\bar{\theta}_{13} = 2^\circ \; \bar{\delta} = 90^\circ$

The SPL and low-γ Beta Beam

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

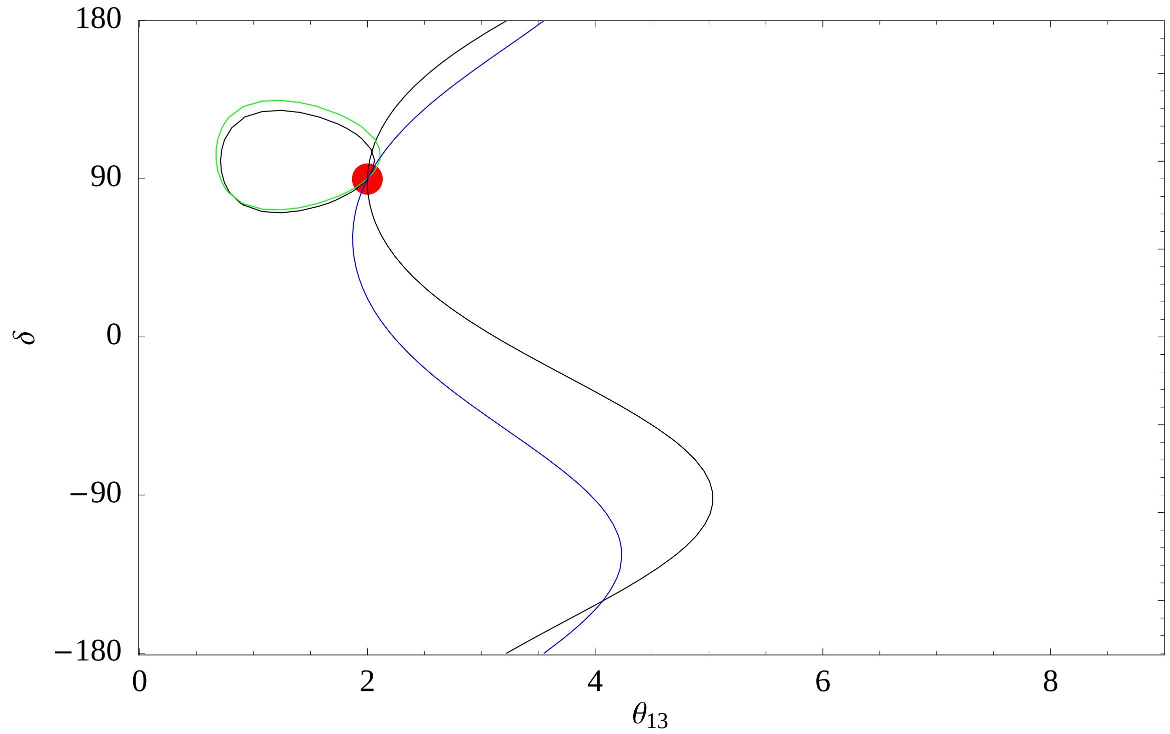
A. Donini *et al.*, hep-ph/0406132



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

The SPL and low-γ Beta Beam

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



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

Conclusions

The next generation of neutrino experiments (beams, first generation superbeams and reactors) will improve our knowledge of the leptonic mixing matrix:

- ▷ mass differences $\Delta m^2_{23}, \Delta m^2_{12}$ at some %;
- ▷ mixing angles θ_{12}, θ_{23} at 10 %;
- ▷ the sign of Δm^2_{23}, if lucky;
- ▷ the value of θ_{13}, if $\theta_{13} > 3^\circ (\sin^2 2\theta_{13} > 0.01)$.

Some (unexpected ?) presents could originate in natural source experiments, in particular from cosmology and supernovae.

Conclusions,2

The precision era in the leptonic mixing will start only with the next-to-next generation: the Neutrino Factory and/or the BetaBeam concepts.

In this phase, we will start
the quest for leptonic CP violation.

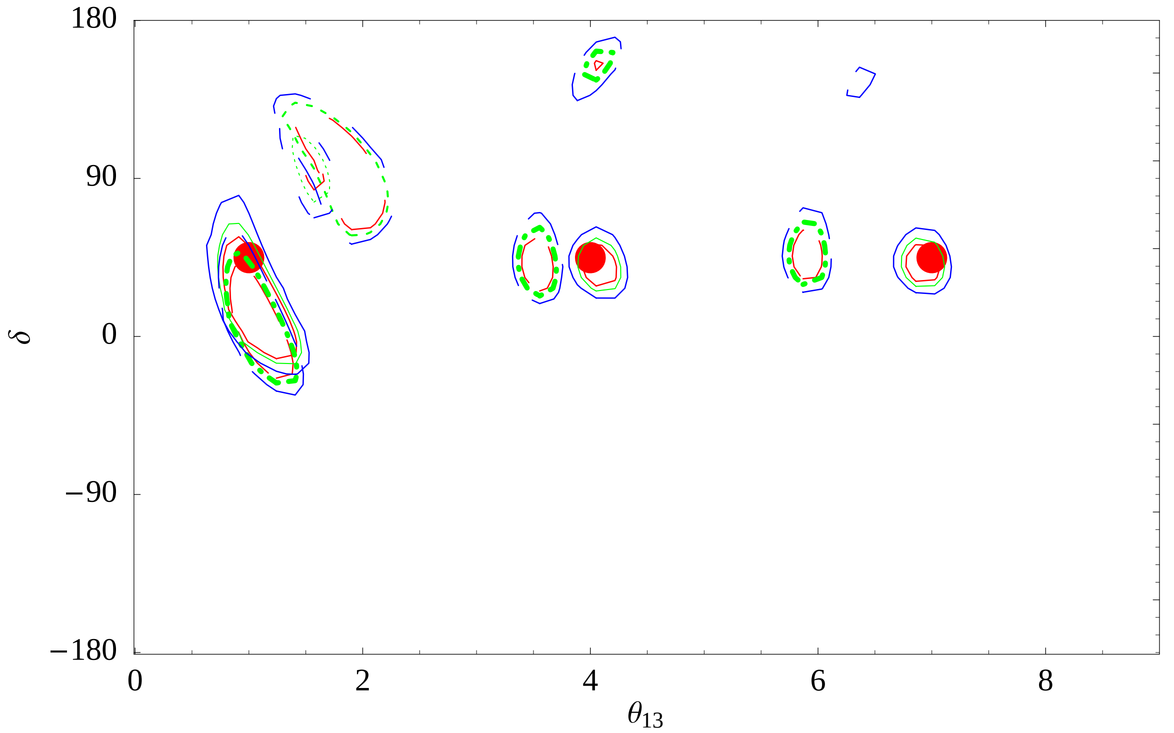
A non-vanishing phase δ is a key ingredient in leptogenesis (the most popular theory for baryogenesis, nowadays).

It is crucial to combine experiments and neutrino sources to solve the severe parameter degeneracy that obstacles a clean measurement of δ.

So what?

Outlook

First possibility: the High-gamma Beta Beam.
Half the statistics at $\gamma_{^{18}Ne} = 2500, \gamma_{^{6}He} = 1500$:



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

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