



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:

$$m_\nu \geq 0.05 \text{ eV} \rightarrow m_t = 178 \text{ GeV}$$

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



Measure of **ALL** parameters in the **Mixing Matrices!**

The leptonic mixing matrix, now

- $|\Delta m_{atm}^2| = (2.6 \pm 0.4) \cdot 10^{-3} \text{ eV}^2$
- $\Delta m_{sol}^2 = (8.3 \pm 0.4) \cdot 10^{-5} \text{ eV}^2$
- $\sin^2 \theta_{23} = (0.33 - 0.68) \text{ at } 3\sigma$
- $\sin^2 \theta_{12} = (0.22 - 0.38) \text{ at } 3\sigma$
- $\sin^2 \theta_{13} \leq 0.041 \text{ at } 3\sigma$
- The sign of Δm_{atm}^2
- 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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 - ★ 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: ${}^6\text{He} \rightarrow \bar{\nu}_e, {}^{18}\text{Ne} \rightarrow \nu_e$

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
	→ 8°	→ 0.08	→ 0.02
CNGS	5°	0.03	0.008
	→ 7°	→ 0.06	→ 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	2.2°	0.006	0.0015
(T2K)	→ 3.3°	→ 0.013	→ 0.0030
NUMI-OA	2°	0.005	0.0010
(NO ν A)	→ 3.5°	→ 0.015	→ 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 $\Delta m_{atm}^2, \Delta m_{sol}^2$ at some %;

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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?

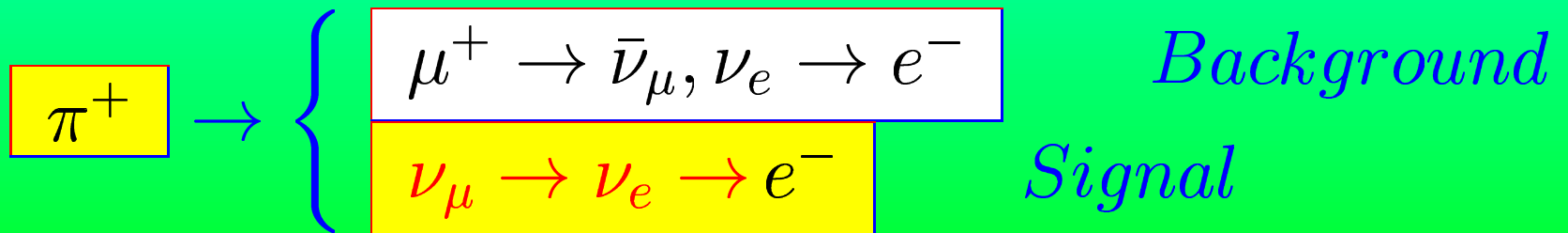
After T2K and NO ν A, we will face a forking path:

- ★ $\nu_{\mu} \rightarrow \nu_e$ 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



The oscillation probability is

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

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

$$+ Z + \dots$$

The (θ_{13}, δ) correlation

The number of signal electrons is:

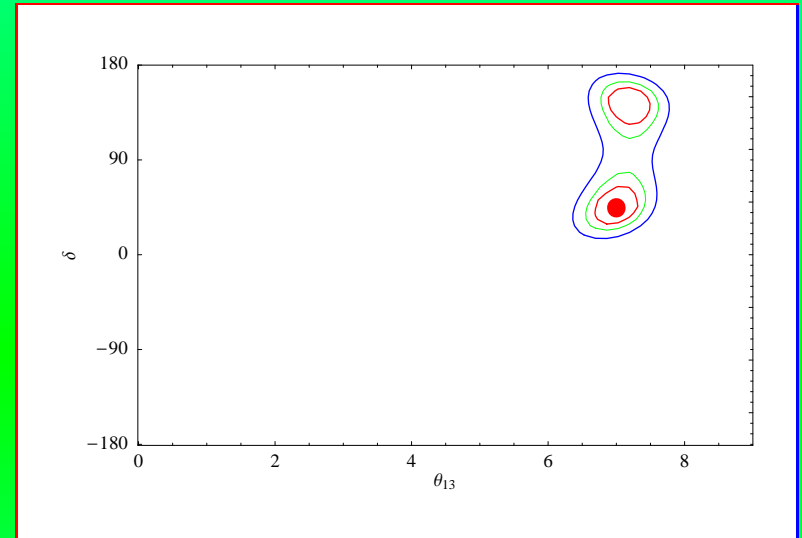
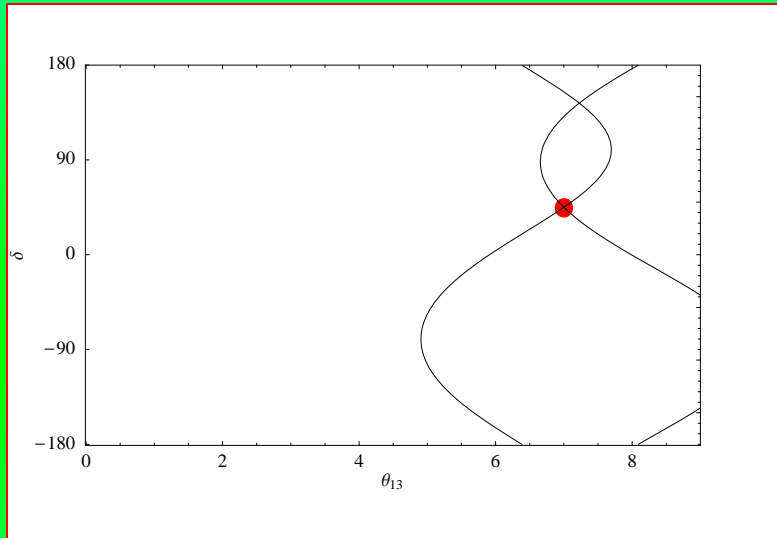
$$N_{e^-}(\bar{\theta}_{13}, \bar{\delta}) = \left\{ \epsilon_e \otimes \sigma_{\nu_e} \otimes P_{\mu e}^+(\bar{\theta}_{13}, \bar{\delta}) \otimes \Phi_{\nu_\mu} \right\}_E^{E+\Delta E}$$

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

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^-



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

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

The (θ_{13}, δ) correlation (2)

The number of signal electrons is:

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

$$N_{\pm}^i(\bar{\theta}_{13}, \bar{\delta}, \bar{s}_{atm}, \bar{s}_{oct}) = N_{\pm}^i(\theta_{13}, \delta, s_{atm}, s_{oct})$$

where

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

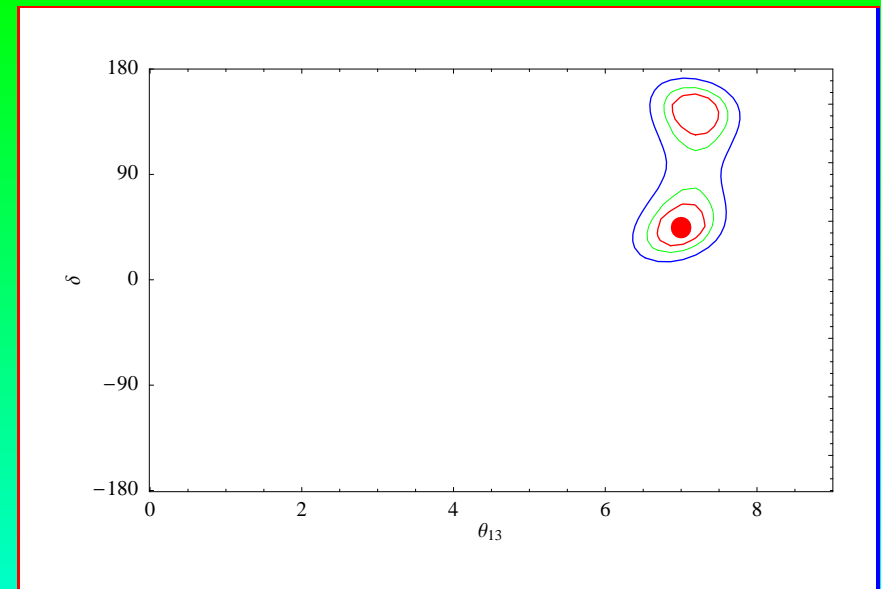
Of other clones

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

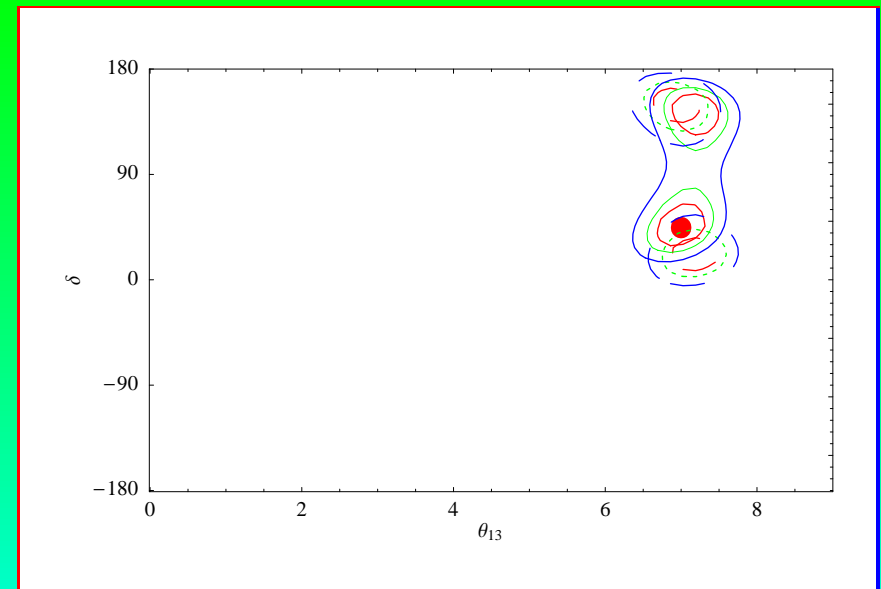
As a third step:

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

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

One more ambiguity:

- ▷ the **sign** clone



Of other clones

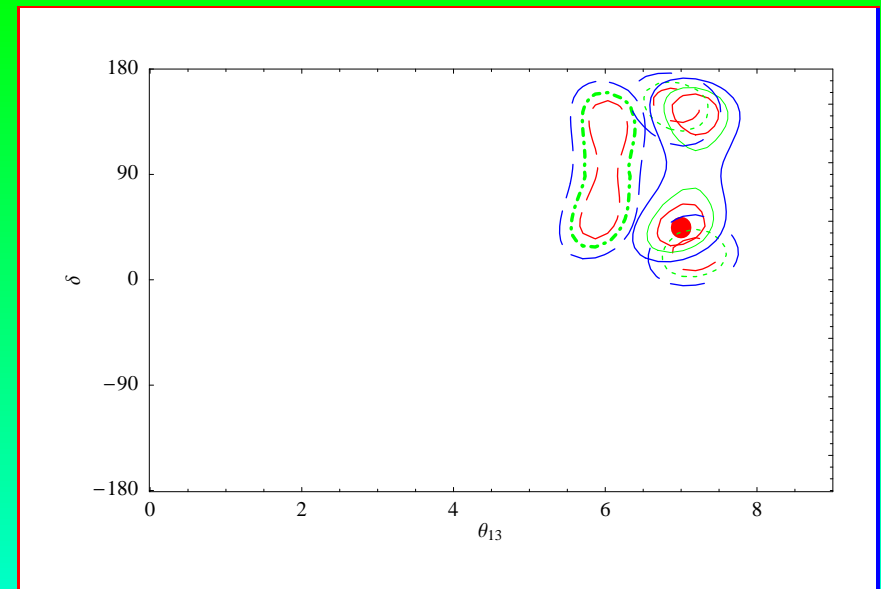
As a second step:

- ▷ $\theta_{23} \neq 45^\circ$
- ▷ 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

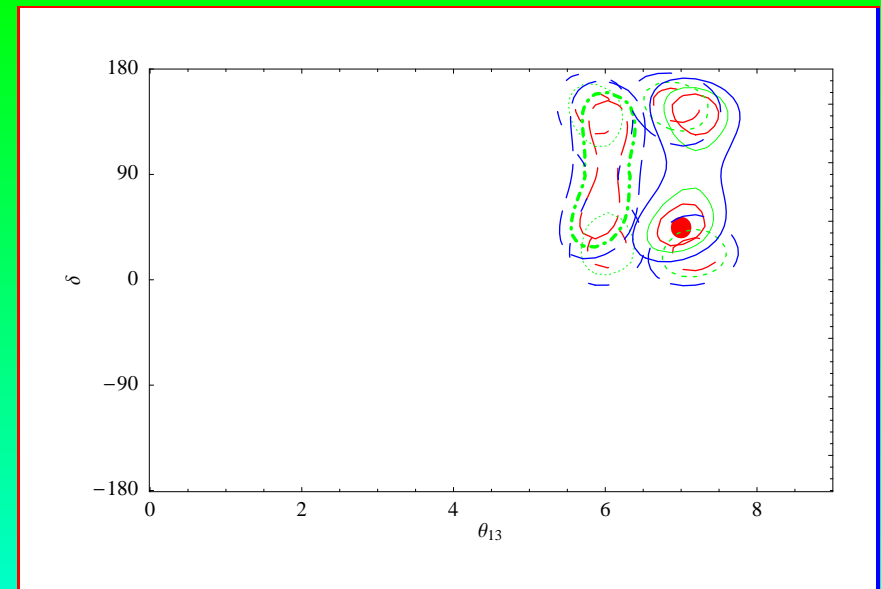
As a fourth step:

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

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

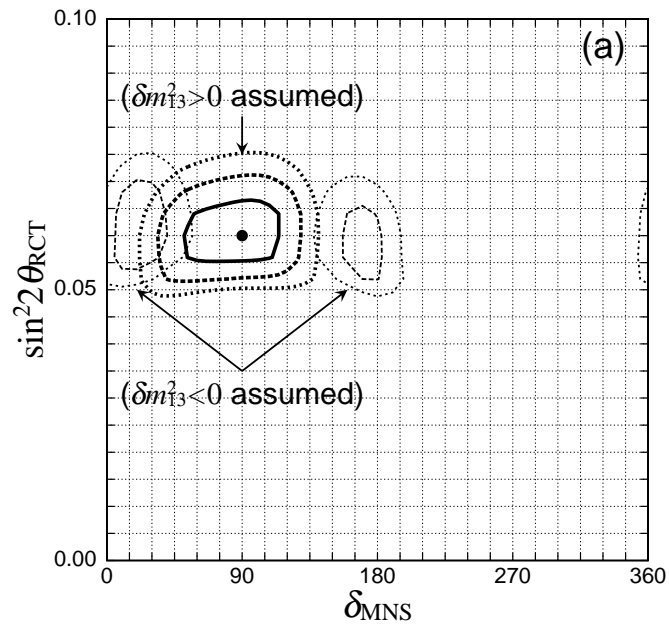
Three more ambiguities:

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



The same at T2-HK

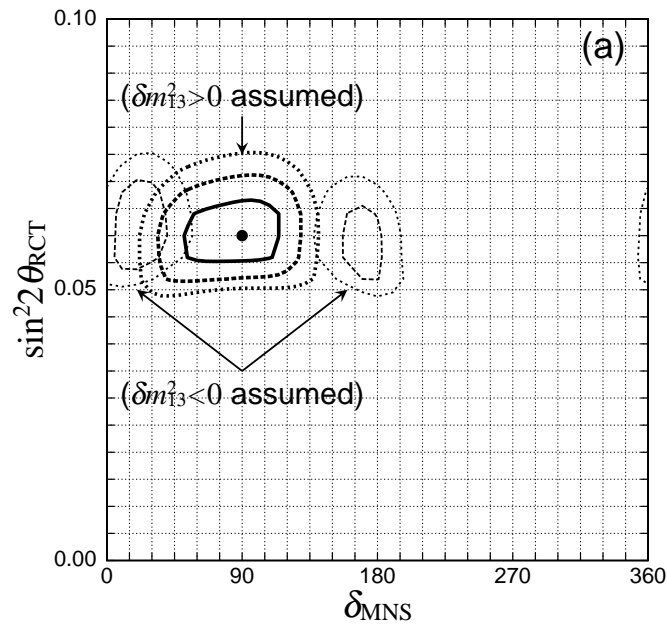
The sign degeneracy



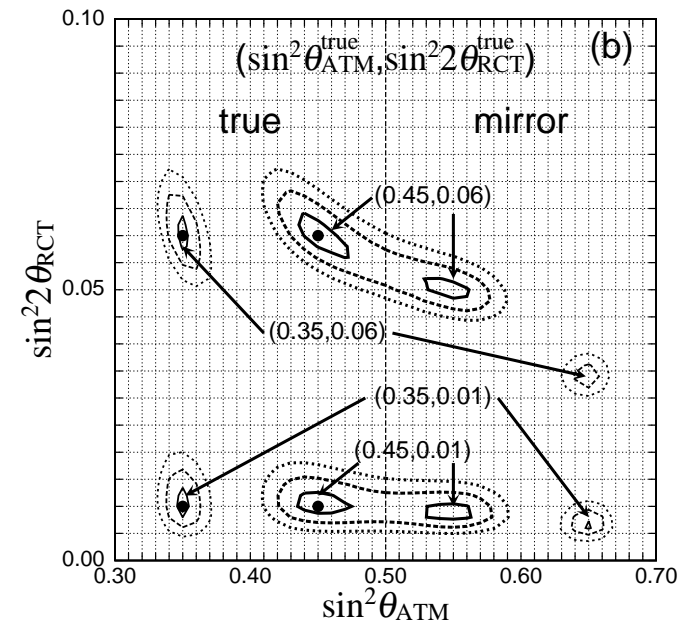
K. Hagiwara, hep-ph/0410229

The same at T2-HK

The sign degeneracy



The octant degeneracy



K. Hagiwara, hep-ph/0410229

The Ultimate Setup

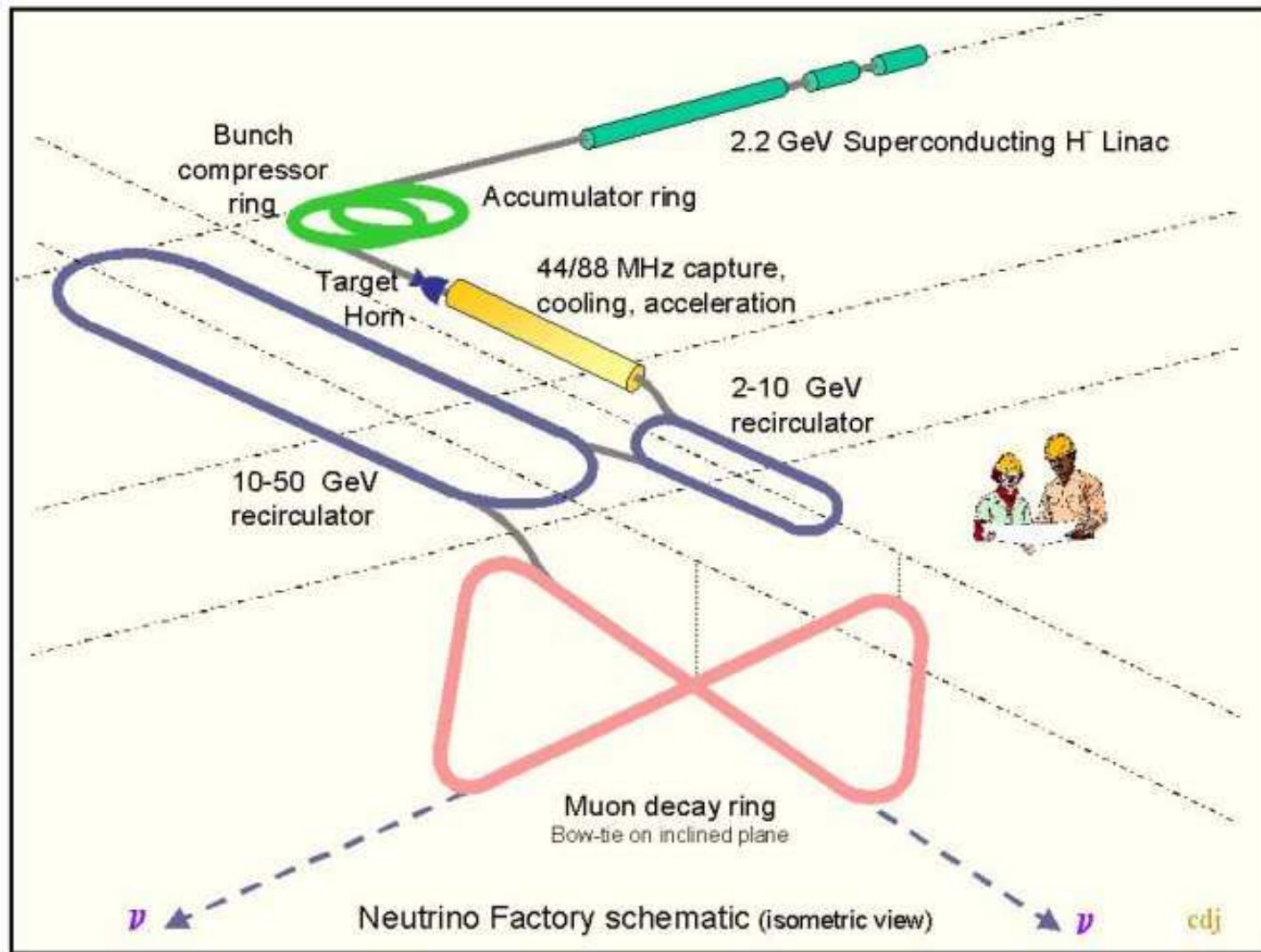
Conventional (super)beams alone are not enough.
We must consider **NEW FACILITIES**.

- ▷ 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



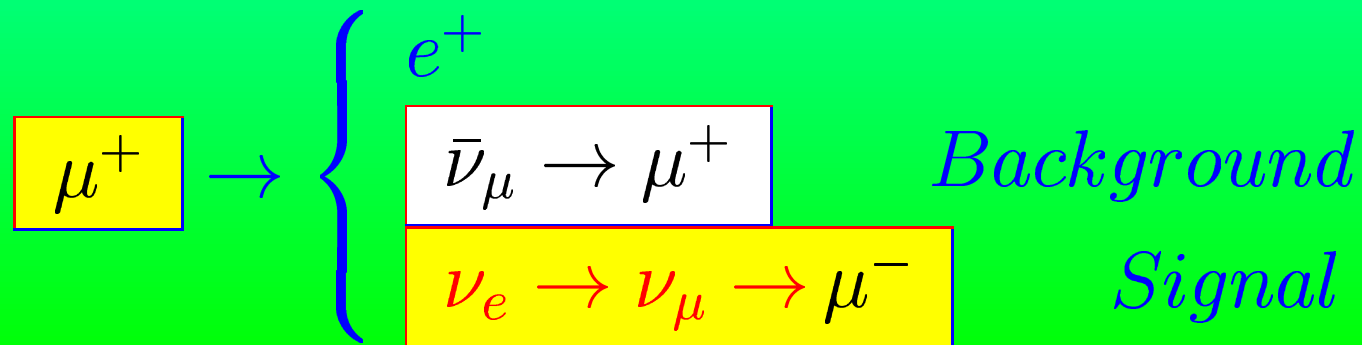
The ν -factory/detectors setup

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

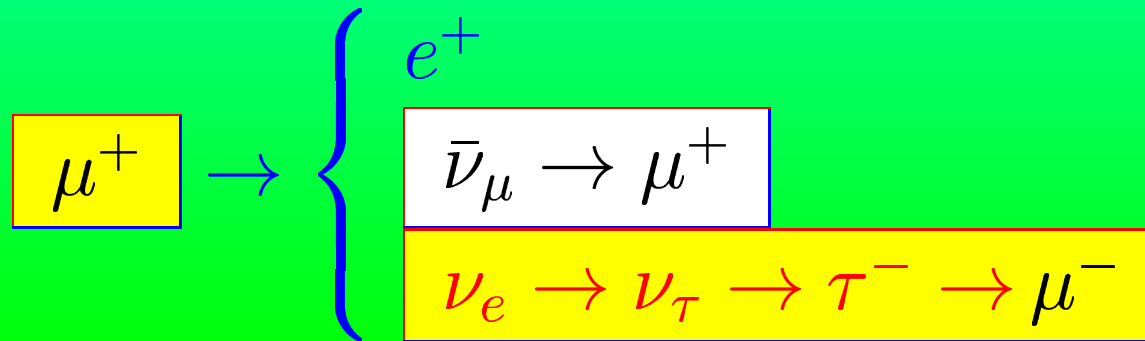


The oscillation probability is

$$P_{e\mu}^\pm = X_\pm \sin^2(2\theta_{13}) + Y_\pm \cos\left(\delta \mp \frac{\Delta_{atm}L}{2}\right) \cos\theta_{13} \sin(2\theta_{13}) + Z + \dots$$

The Silver channel: ν -factory

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



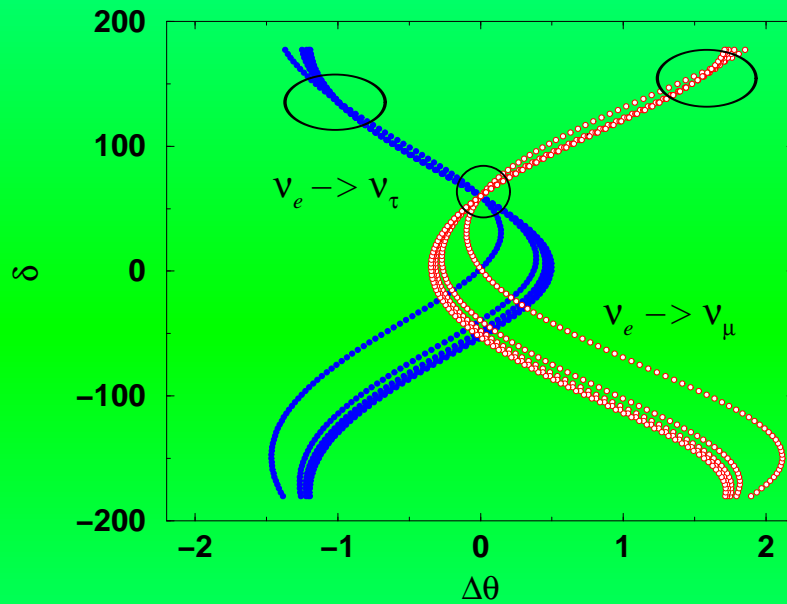
The oscillation probability is

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

$$-Y_\pm^\tau \cos\left(\delta \mp \frac{\Delta_{atm}L}{2}\right) \cos\theta_{13} \sin(2\theta_{13}) \\ +Z^\tau + \dots$$

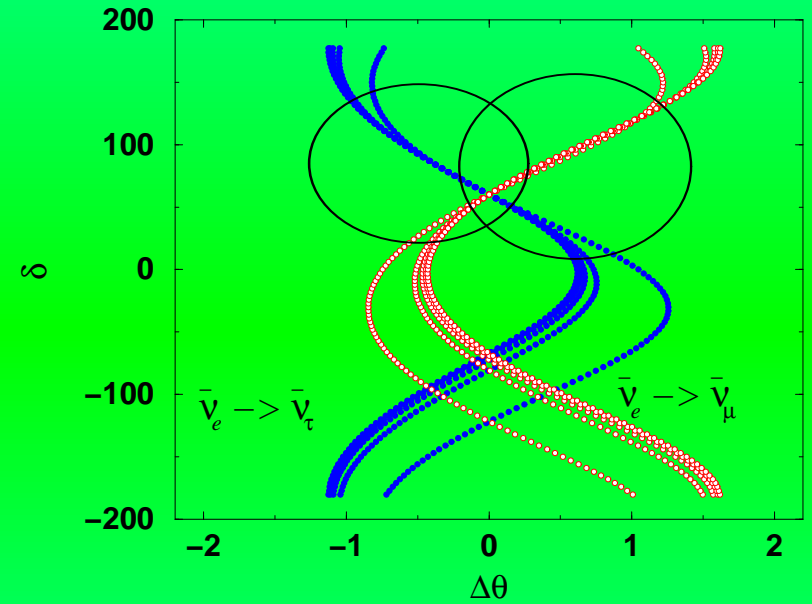
The intrinsic clones

$L = 732 \text{ Km}$



Neutrinos

$L = 732 \text{ Km}$



Antineutrinos

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

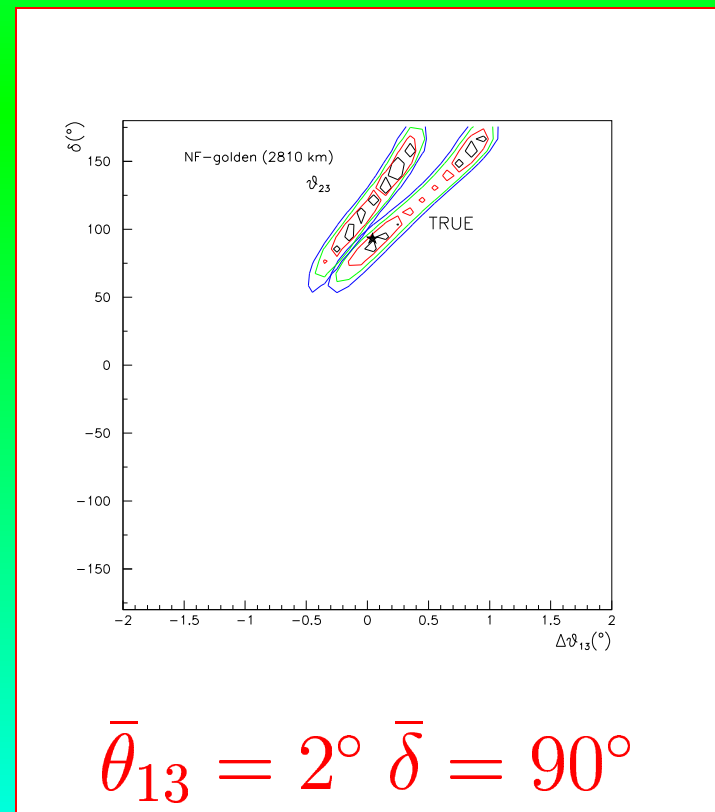
$$\Delta\theta = \theta_{13} - \bar{\theta}_{13}$$

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



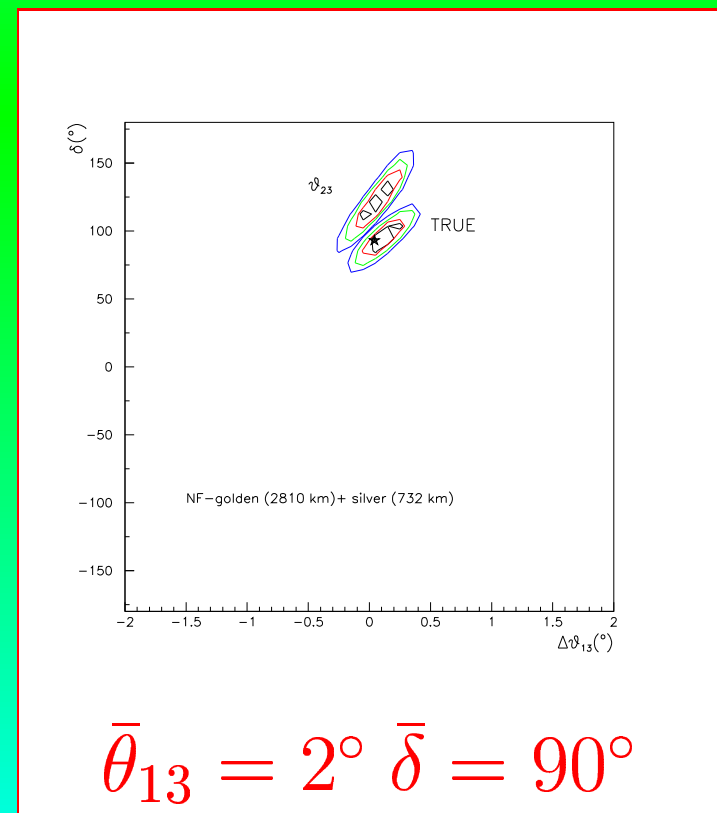
Two detectors

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

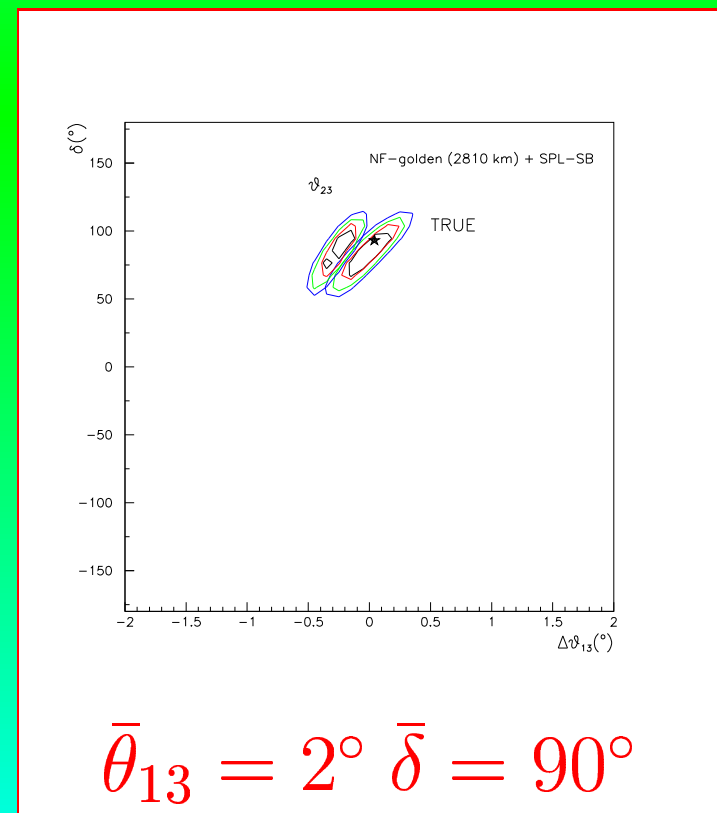


Two detectors

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

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

- 40 Kton MID
- 400 Kton WC

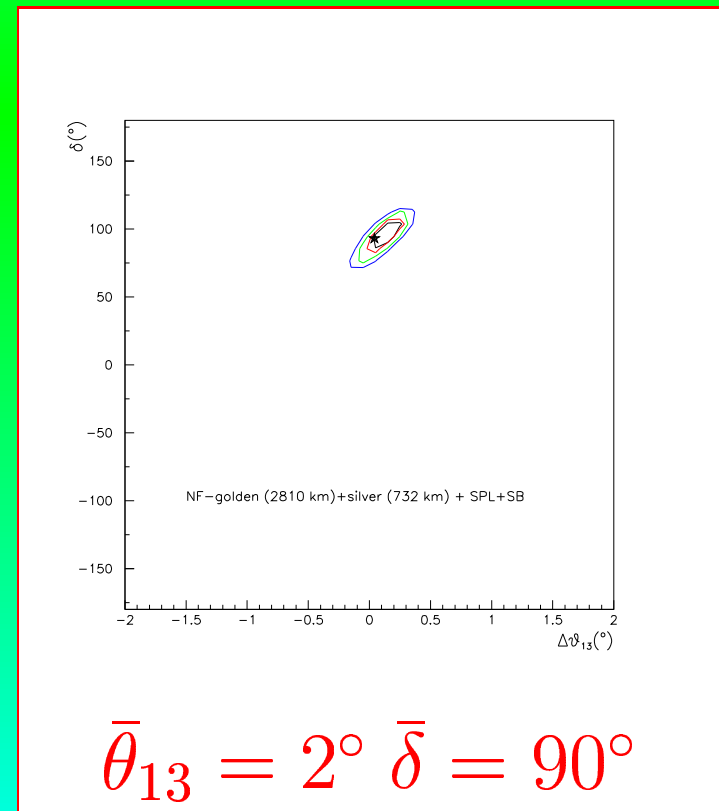


The Three Detectors

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



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

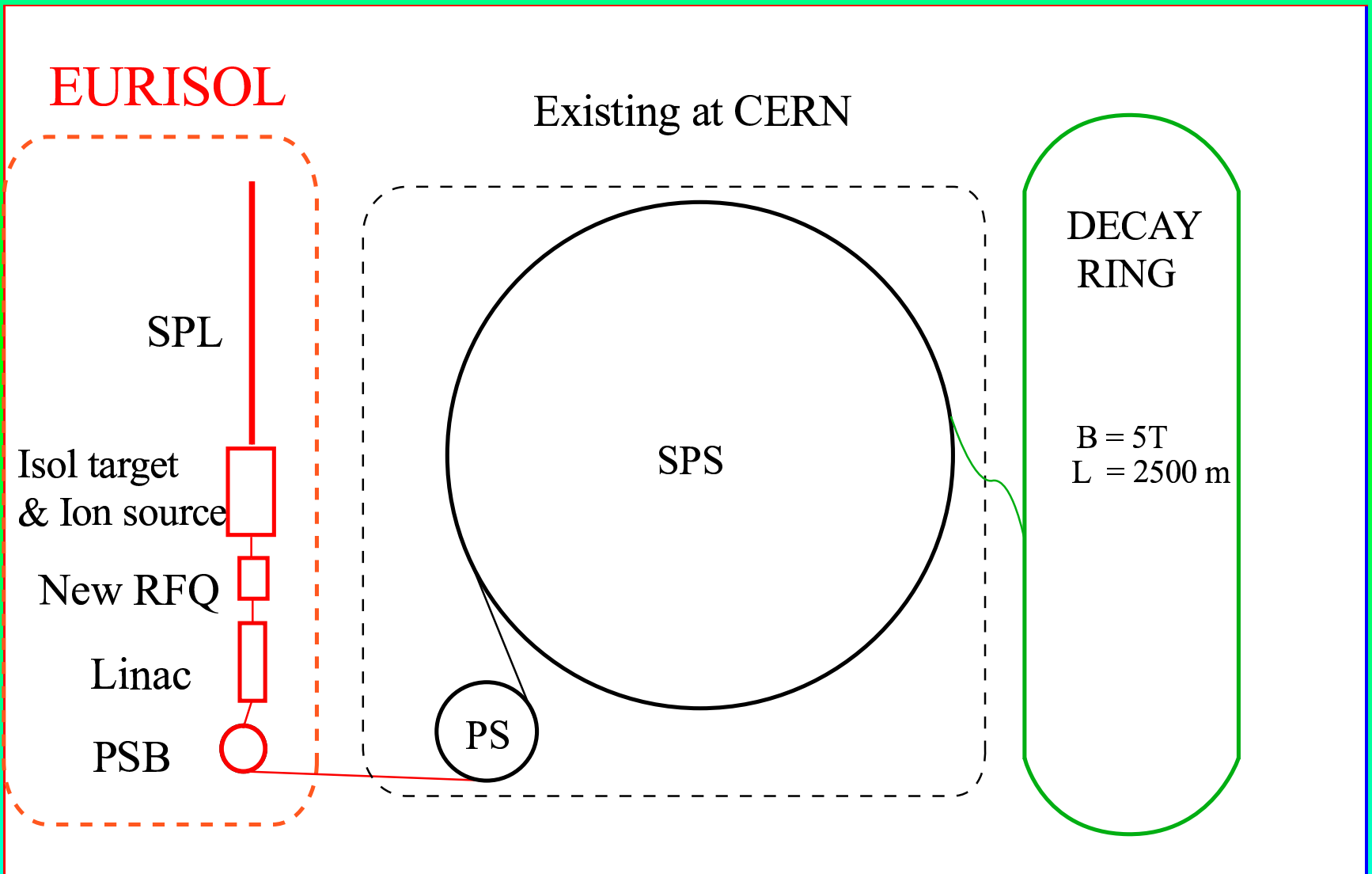
J. Burguet-Castell *et al.*, hep-ph/0312068

- very high- γ BB

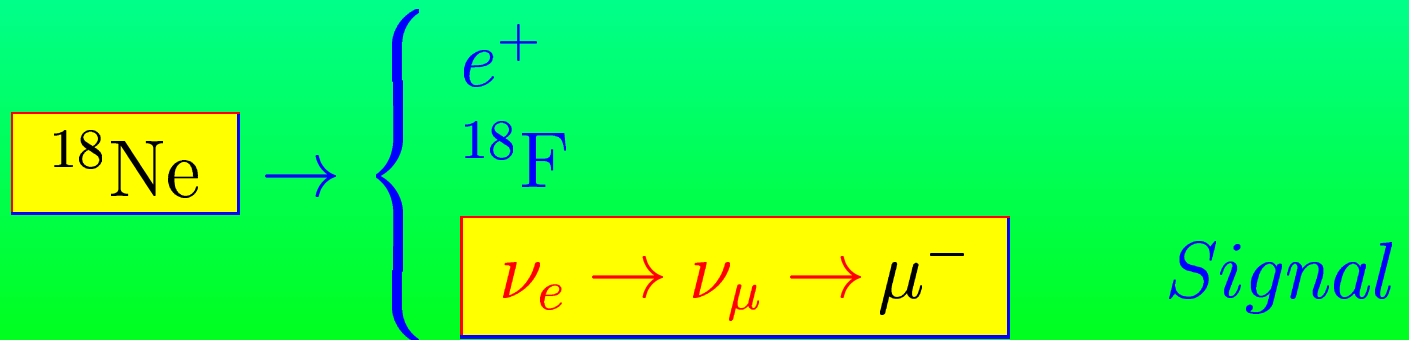
P. Migliozzi and F. Terranova, hep-ph/0405081

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

The Beta-Beam at CERN



The Golden channel: β -beam



The oscillation probability is

$$P_{e\mu}^\pm = X_\pm \sin^2(2\theta_{13}) \\ + Y_\pm \cos\left(\delta \mp \frac{\Delta_{atm}L}{2}\right) \cos\theta_{13} \sin(2\theta_{13}) \\ + Z + \dots$$

The SPL and low- γ Beta Beam

CERN design for 2.2 GeV superbeam
and a low- γ β -beam:

$$\gamma = 60 \text{ for } {}^6\text{He};$$

$$\gamma = 100 \text{ for } {}^{18}\text{Ne}$$

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

UNO Collaboration, hep-ex/0005046;

D. Casper, Nucl. Phys. Proc. Suppl. 112 (2002) 161.

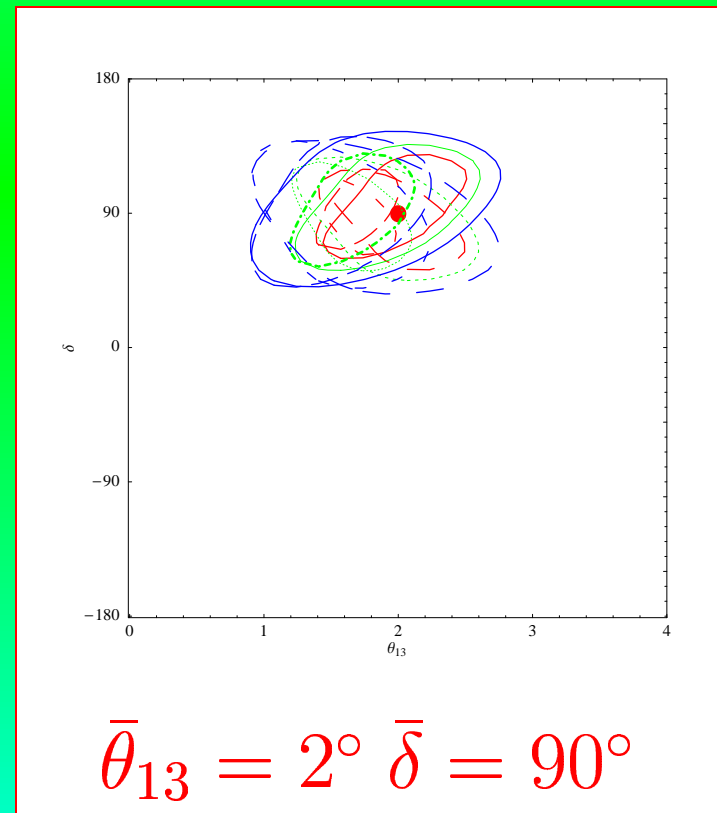
The SPL and low- γ Beta Beam

Consider the $\nu_e \rightarrow \nu_\mu$ at the BB:

one massive Water Cherenkov, with baseline $L = 130$

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

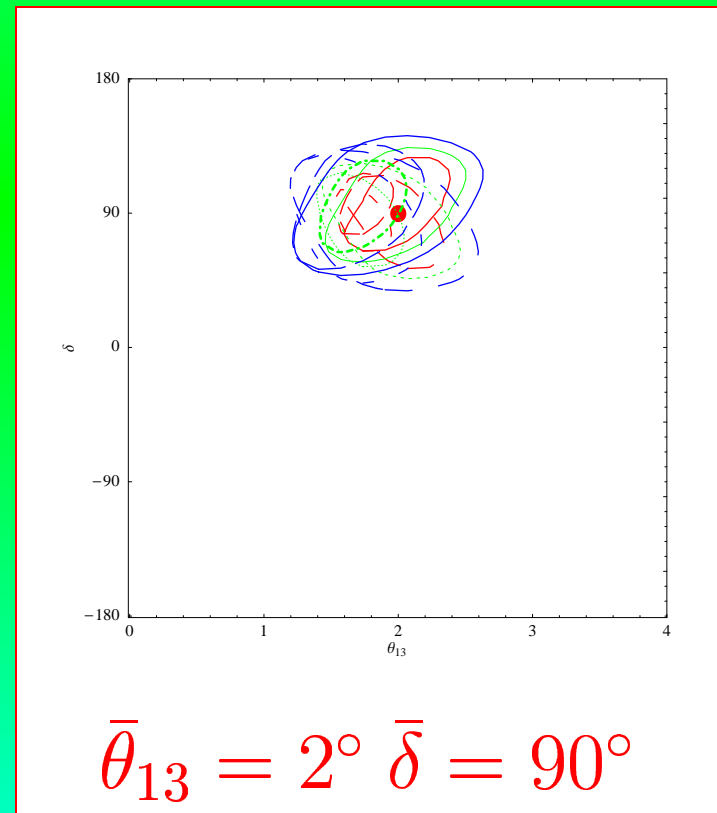
- 440 Kton WC-BB



The SPL and low- γ Beta Beam

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

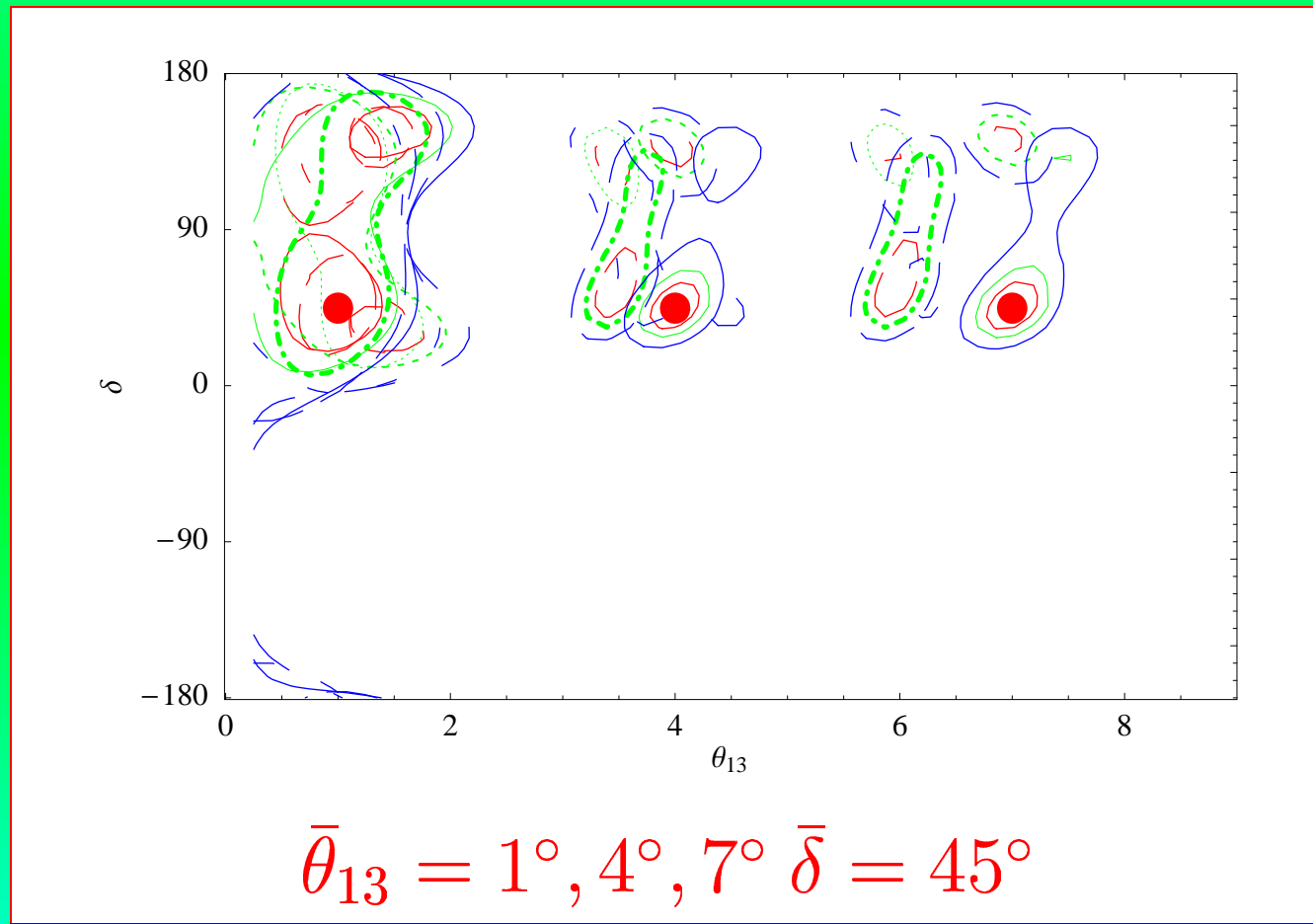
- 440 Kton WC-BB
- 440 Kton WC-SPL



The SPL and low- γ Beta Beam

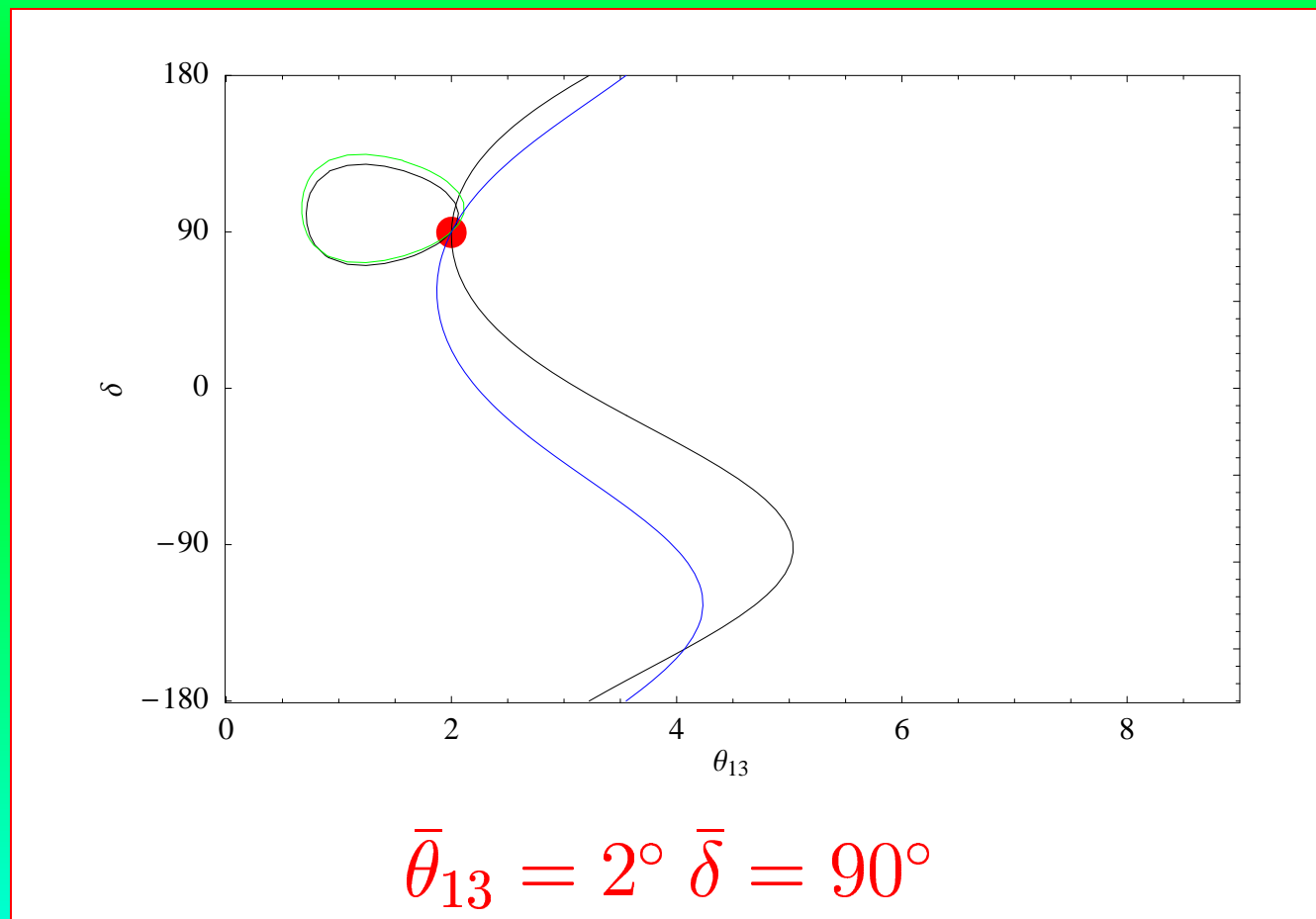
This is the general situation for $\delta \neq 90^\circ$.

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



The SPL and low- γ Beta Beam

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



The medium- γ Beta Beam

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

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

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

The same detector:

- 440 Kton Water Cherenkov (WC)

$$L = 732 \text{ Km (Gran Sasso or Soudan)}$$

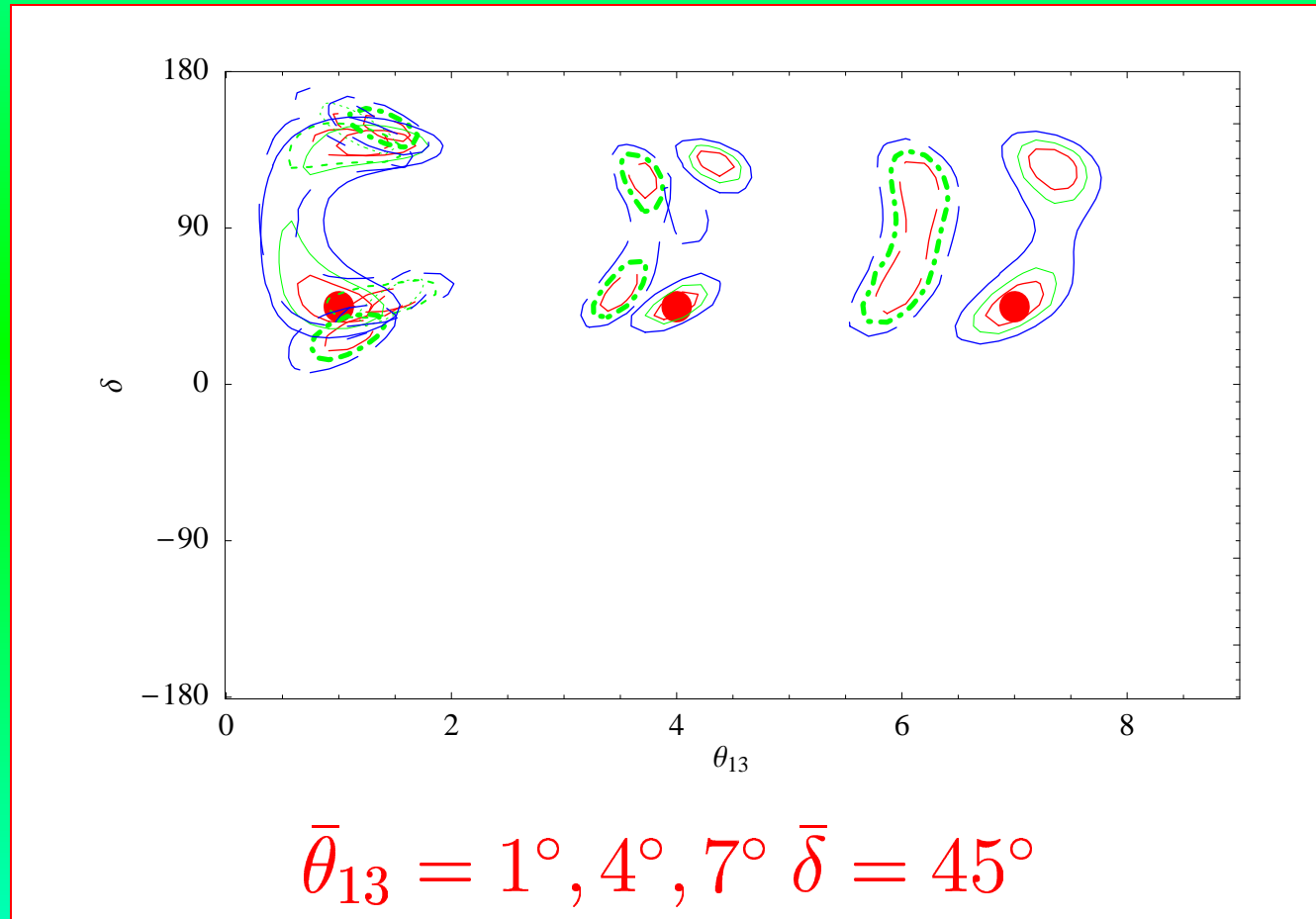
UNO Collaboration, hep-ex/0005046;

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

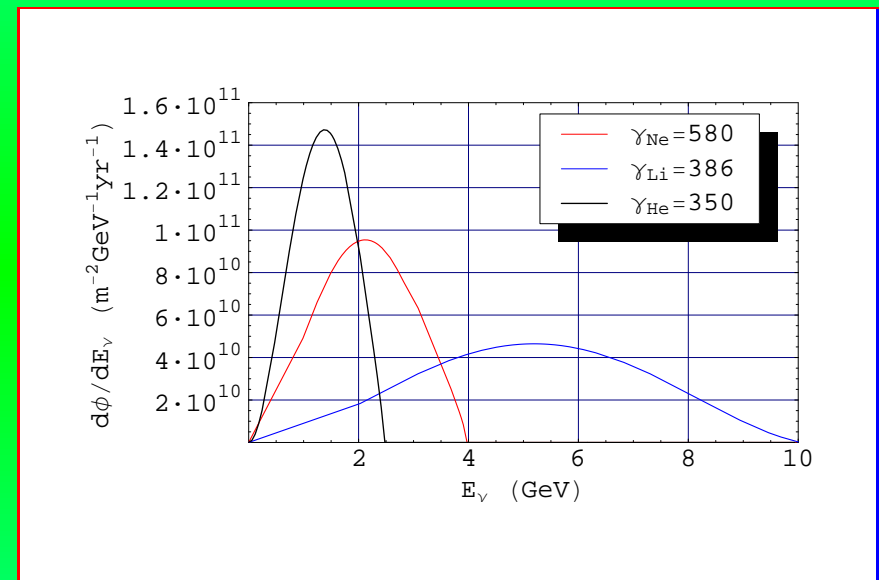
The medium- γ Beta Beam



The medium- γ Beta Beam

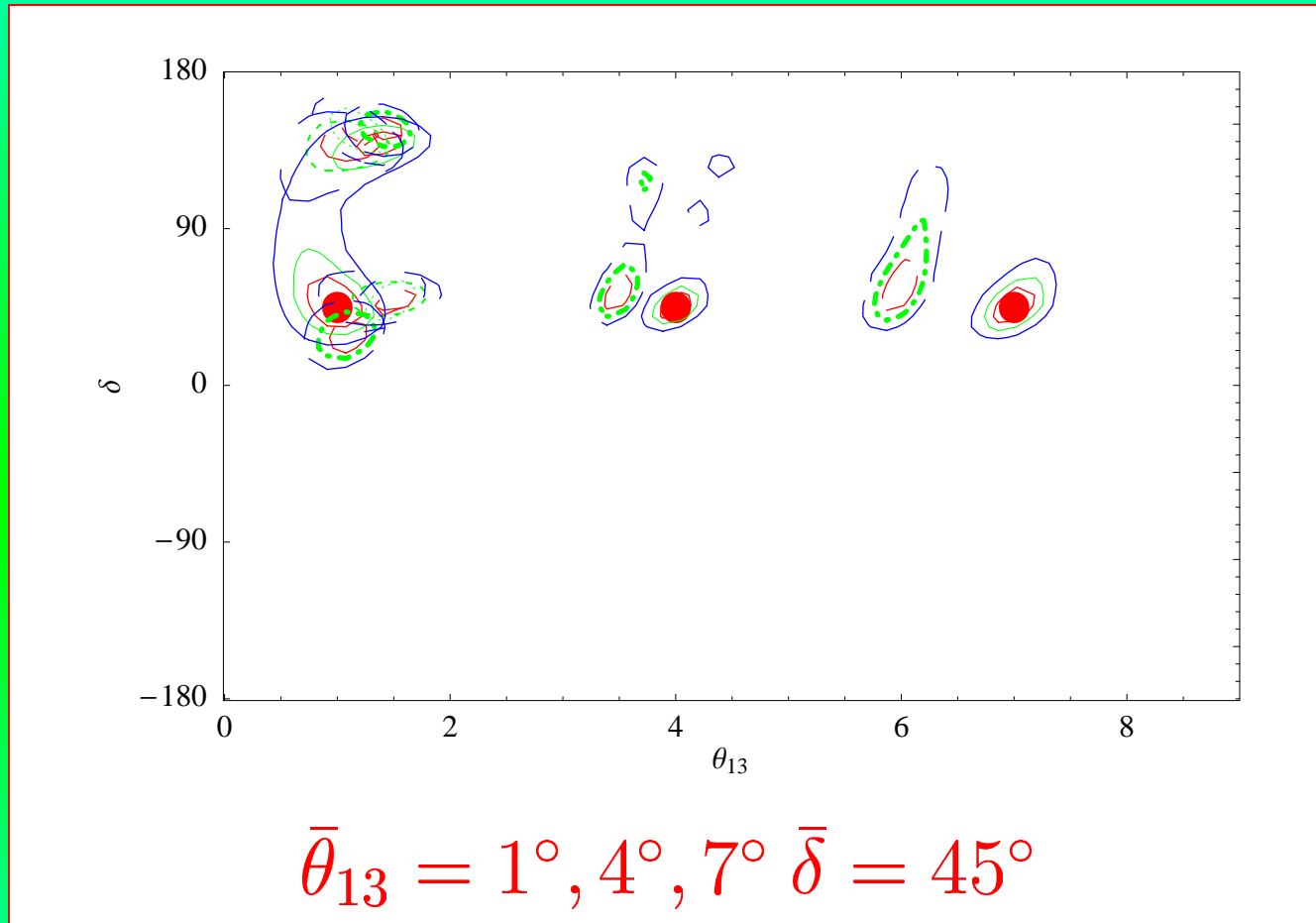
${}^8\text{Li}$ is a good alternative to ${}^6\text{He}$:
higher production rate, same lifetime.

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



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

The ions cocktail at medium- γ



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

The high- γ Beta Beam

If (using the LHC?) we achieve the energy:

$$\gamma = 1500 \text{ for } {}^6\text{He}; \quad \gamma = 2500 \text{ for } {}^{18}\text{Ne}$$

then we can use both the golden and silver channels:

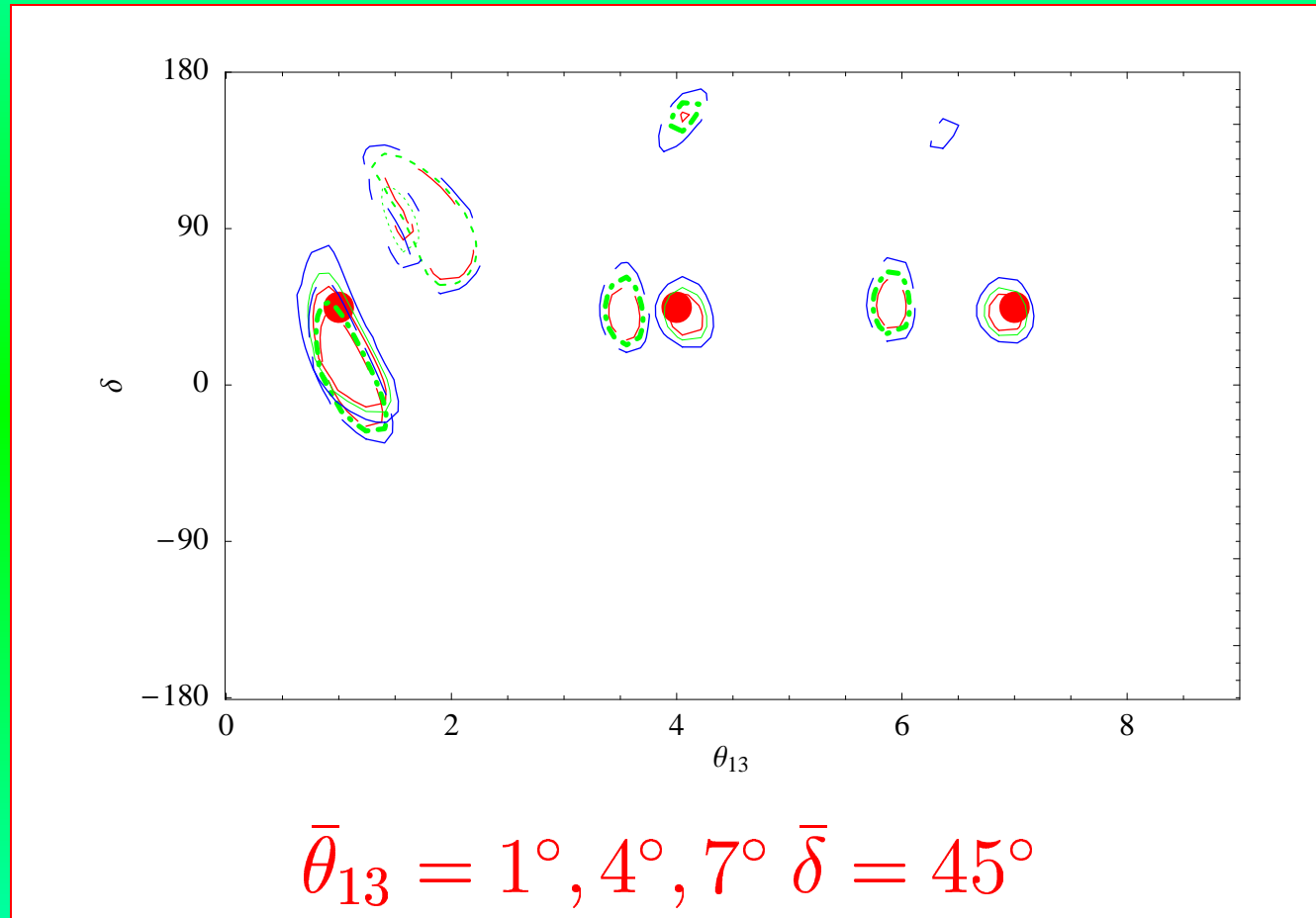
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 $L = 732 \text{ Km}$ (Gran Sasso) or $L = 2810 \text{ Km}$
D. Autiero *et al.*, hep-ph/0305185; NuFact03, New York

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 $\gamma_{^{18}\text{Ne}} = 2500$, $\gamma_{^6\text{He}} = 1500$:



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

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_{atm}^2** 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

The BetaBeam option must be studied carefully, taking advantage of existing resources.

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Conclusions, 2

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- ▷ The only carefully studied option, **low- γ BetaBeam** with $L = 130$ Km is **not competitive** with SB-Phase II. **Room for improvement!**
- ▷ **Medium- γ BetaBeam** with $L = 732$ Km is **better than SB-Phase II**.
Do binning without energy resolution:
ions cocktail.

Conclusions, 2

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- ▷ **Medium- γ BetaBeam** with $L = 732$ Km is **better than SB-Phase II**.
Do binning without energy resolution:
ions cocktail.
- ▷ **High- γ BetaBeam** is the **only alternative** to **Neutrino Factory**. Technically possible?