GOLDEN & SILVER CHANNELS AT A NEUTRINO FACTORY

O. Mena

Fermilab Theoretical Physics Department

APS Neutrino Study

Neutrino Factory & Beta Beams Working Group

3-4 March, Argonne National Laboratory

Based on:

- **A. Cervera, A. Donini, M. B. Gavela, J. J. Gómez Cádenas, P. Hernández, O. M and S. Rigolin, *"Golden measurements at a neutrino factory,"* Nucl. Phys. B579, (2000) 17; Erratum-ibid. B593, (2001) 731.**
- **J. Burguet-Castell, M. B. Gavela, J. J. Gómez-Cádenas, P. Hernández and O. M,*"On the measurement of leptonic CP violation,"* Nucl. Phys. B608, (2001) 301.**
- **A. Donini, D. Meloni and P. Migliozzi, *"The silver channel at the neutrino factory,"* Nucl. Phys. B 646, (2002) 321.**
- **O. M,*"Puzzling out neutrino mixing through golden and silver measurements,"* hep-ph/0305146.**
- **D. Autiero** *et al.*, ***"The synergy of the golden and silver channels at the Neutrino Factory,"* hep-ph/0305185.**
- **In preparation: A. Donini** *et al*.

MOTIVATIONS $\&$ GOALS

- In the SM neutrinos (ν's) are massless: no mixing nor CP Violation in the leptonic sector.
- However SK + SNO + KamLAND indicate that ν's change flavor: $\Delta m^2_{atm} \sim 1 \times 10^{-3}$ eV^2, $\Delta m^2_{sol} \sim 1 \times 10^{-4}$ eV^2 , both with large mixing angles.
- **ν metamorphosis $\longrightarrow$ New Physics Beyond the SM (NP) + New energy scale Λ**
- **Leptonic CP Violation $\longrightarrow$ Matter-Antimatter Asymmetry of the Universe**

$\Downarrow$

Precise measurement of ν mixing parameters $+$ Leptonic CP Violation

Neutrino Physics is entering in a precision era

$\Downarrow$

Key to these goals: Neutrino Factory!

Outline

- **Status of ν mixing and Pending Questions**
- **ν- Factories**:

1. **The golden channel:** $\nu_e \longrightarrow \nu_\mu$
   - **Simultaneous determination of δ-CP and θ_{13}?**
   - **Not unambiguously!: Degenerate solutions**

$$\Downarrow$$

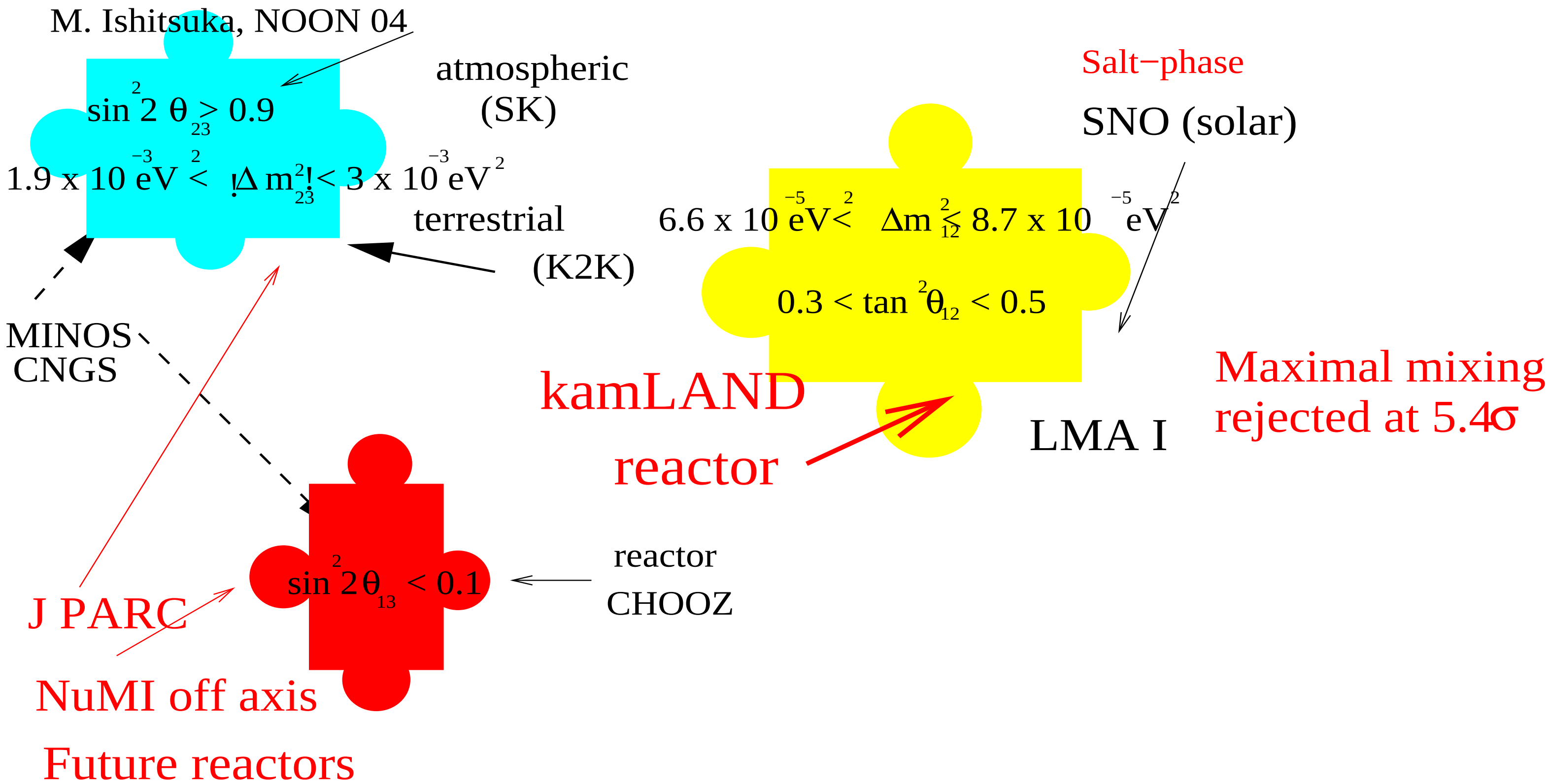
CLONES : The problem...

2. **The *silver* channel:** $\nu_e \longrightarrow \nu_\tau$
   - **First motivation: *Intrinsic clones***
   - **Second motivation: θ_{23} Octant clones**

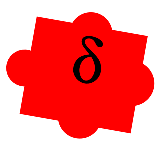
$$\Downarrow$$

The solution!

Status of the ν mixing puzzle (@90% C.L's)



δ ?

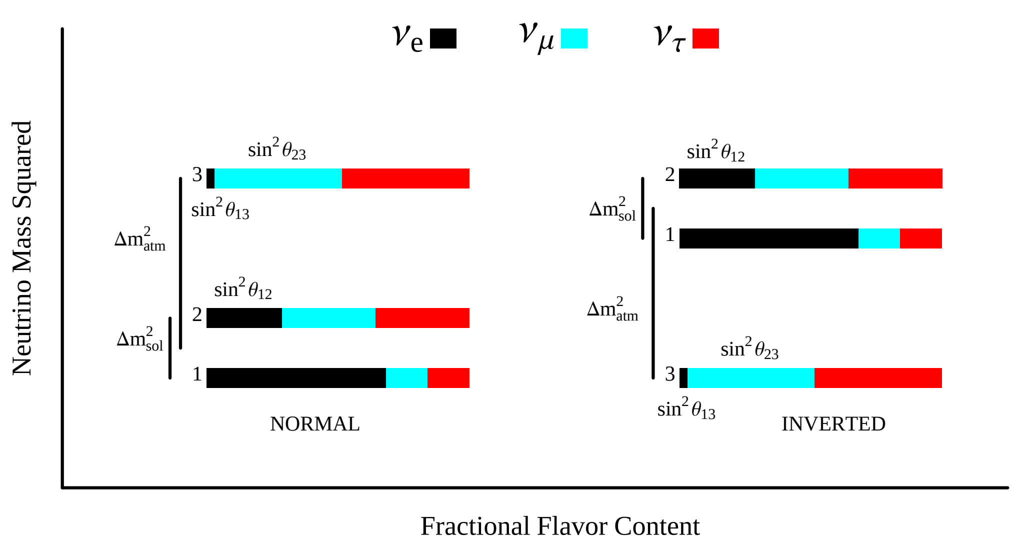


CURRENTLY UNOBSERVABLE!

However, despite of the expected progress, in several years from now, may remain unknown:

1. **The value of θ_{13}:**
   - **First priority: Reactor & Superbeams!**
   - **Reactors can set the scale of θ_{13}.**
     (http://www.hep.anl.gov/minos/reactor13/white.html; H. Minakata *et al.*, Phys. Rev. D **68**, 033017 (2003); P. Huber *et al.*, Nucl. Phys. B **665**, 487 (2003); M. H. Shaevitz and J. M. Link, hep-ex/0306031.)
   - **Future telescopes, in a decaying astro-ν scenario.**
     J. F. Beacom *et al.*, hep-ph/0309267.

2. **The ordering of the mass spectrum: matter effects!**

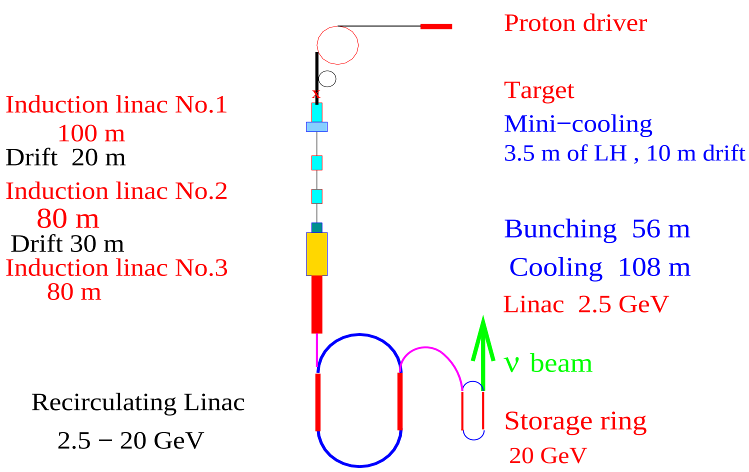


3. **The existence of leptonic CP Violation!**

Neutrino Factory

S. Geer, Phys. Rev. D **57**, (1998) 6989

- ν **beams of precise composition** $\sim \mathcal{O}(0.1\%)$ **from muon decays:** $\mu^{\pm} \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu.)$
  A. Broncano and O. M, Eur. Phys. J. C **29** (2003) 197.
- **The** ν **flux is** $\sim 10^4$ **times the conventional flux**.
- ν_e **and** $\overline{\nu}_e$ **beams in addition to** ν_μ **and** $\overline{\nu}_\mu$ **beams.**

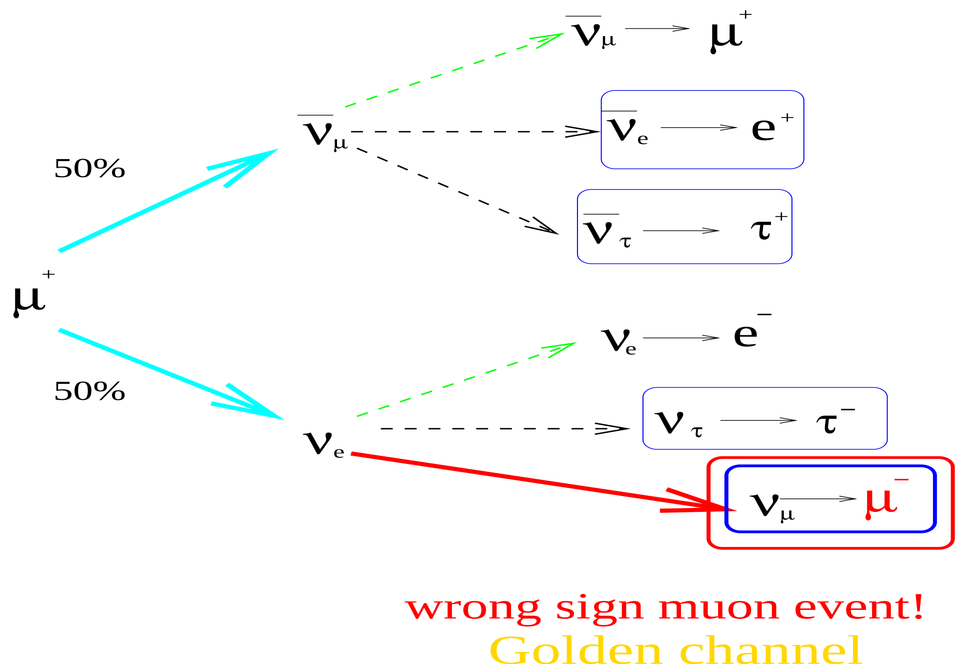


R. Raja, hep-ex/0402022.

Our setup

A. Cervera *et al.*, Nucl. Phys. **B579**, (2000) 17; Erratum-ibid. **B593**, (2001) 731.

- 3 **baselines:** 732 **Km,** 2810 **Km**, 7332 **km.**
- 10^{21} μ^+ **AND** μ^- **of** 50 **GeV (FIVE 10 GeV bins).**
- **Realistic efficiencies and backgrounds have been included for a** 40 **Kton iron magnetized calorimeter detector (MID).**



S. Geer, Phys. Rev. **D57**, (1998).

The main goal of neutrino factory is to measure simultaneously

δ**-CP and** θ_{13}

through

$P(\nu_e \rightarrow \nu_\mu)$ **and** $P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$

by searching for wrong sign muons for both polarities.

A. De Rújula, M. B. Gavela and P. Hernández, Nucl. Phys. **B547**, (1999).

WE EXPAND AT SECOND ORDER IN $\frac{\Delta m^2_{12}}{\Delta m^2_{13}}$ and θ_{13}, IN VACUUM APPROX.:

A. Cervera, A. Donini, M. B. Gavela, J. J. Gomez Cadenas, P. Hernandez, O. M and S. Rigolin, Nucl. Phys. B **579** (2000) 17.

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s^2_{23}\ \sin^2 2\theta_{13}\ \sin^2\frac{\Delta m^2_{13}L}{4E} \longleftarrow \text{Atmos}$$

$$+\ c^2_{23}\ \sin^2 2\theta_{12}\ \sin^2\frac{\Delta m^2_{12}L}{4E} \longleftarrow \text{Solar}$$

$$+\ \tilde{J}\ \cos\left(\pm\delta - \frac{\Delta m^2_{13}L}{4E}\right)\frac{\Delta m^2_{12}L}{4E}\sin\frac{\Delta m^2_{13}L}{4E} \longleftarrow \text{Int}$$

$$\tilde{J} \equiv \cos\theta_{13}\ \sin 2\theta_{13}\ \sin 2\theta_{23}\ \sin 2\theta_{12} \sim 2\sin\theta_{13}.$$

By measuring $P_{\nu_e\nu_\mu}$ and $P_{\bar{\nu}_e\bar{\nu}_\mu}$

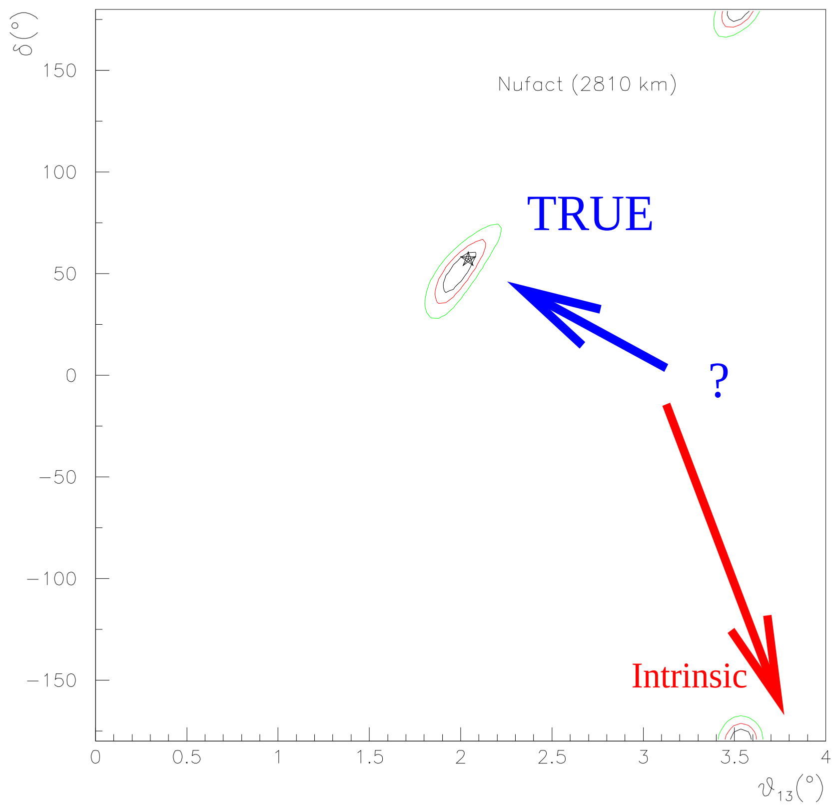
determine unambiguously at fixed E_ν, L

δ-CP and θ_{13}?

Solar sector within the LMA-MSW, $\theta_{23} = 45°$, $|\Delta m^2_{23}| = 3 \times 10^{-3}$ eV^2.

Matter effects included, 68.5%, 90% and 99% C.L

At $\mathcal{O}(3000km)$, and central values: $\delta = 54°$, $\theta_{13} = 2°$:



NO!

J. Burguet-Castell, M. B. Gavela, J. J. Gómez-Cádenas, P. Hernández and O. M, Nucl. Phys. **B608**, (2001) 301.

(θ_{13}', δ') **are fake solutions of:**

$$\left.\begin{array}{l} P_{\nu_e\nu_\mu}(\theta_{13}', \delta') = P_{\nu_e\nu_\mu}(\theta_{13}, \delta) \\ P_{\bar\nu_e\bar\nu_\mu}(\theta_{13}', \delta') = P_{\bar\nu_e\bar\nu_\mu}(\theta_{13}, \delta) \end{array}\right\}$$ **at fixed E_ν and L.**

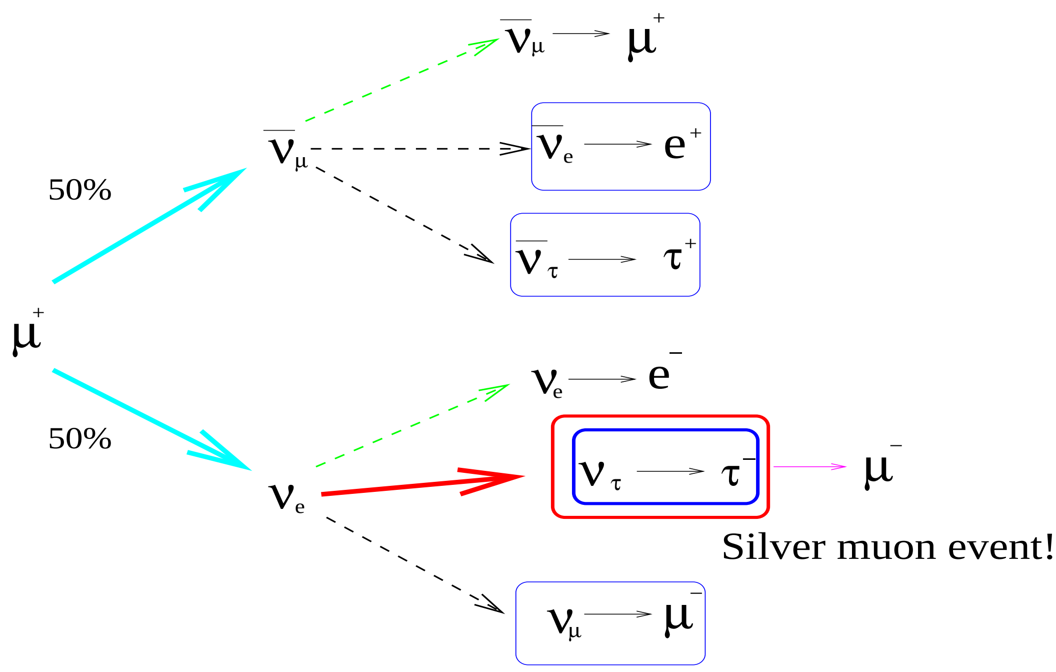
A lot of work devoted to resolve them through E_ν, L...

First motivation

To look for an independent appearance channel:

"Silver channel", $\nu_e \to \nu_\tau$.

(A. Donini *et al.*, Nucl. Phys. B **646**, 321 (2002)).



A. Cervera, A. Donini, M. B. Gavela, J. J. Gomez Cadenas, P. Hernandez, O. M and S. Rigolin, Nucl. Phys. B **579** (2000).

$$P_{\nu_e\nu_\tau(\bar{\nu}_e\bar{\nu}_\tau)} = s_{23}^2 \, \sin^2 2\theta_{13} \, \sin^2 \frac{\Delta m_{13}^2 L}{4E}$$

$$+ \, c_{23}^2 \, \sin^2 2\theta_{12} \, \sin^2 \frac{\Delta m_{12}^2 L}{4E}$$

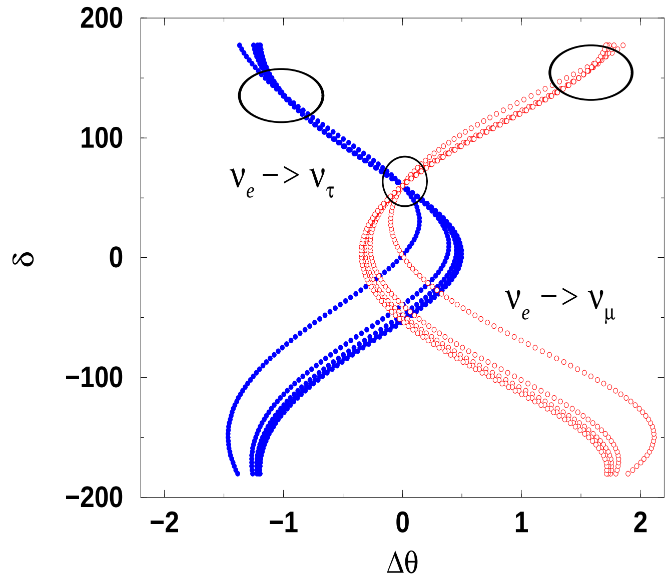
$$\rightarrow \; - \; \tilde{J} \, \cos\left(\pm\delta - \frac{\Delta m_{13}^2 L}{4E}\right) \frac{\Delta m_{12}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E}$$

Interference term changes sign!

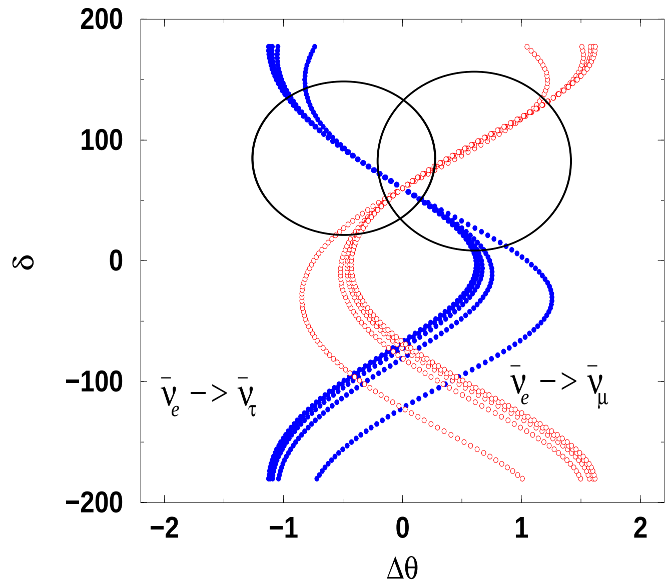
for golden and silver channels.

Equiprobabilities for L=732 km and $\delta = 60°$, $\theta_{13} = 5°$.

μ^+



μ^-



$\tau \to \mu$ **show a different** (θ_{13}, δ)**-correlation than** μ **from** $\nu_e \to \nu_\mu$

D. Autiero *et al.*, hep-ph/0305185.

Silver muons signal

A. Donini, D. Meloni and P. Migliozzi, Nucl. Phys. B **646**, (2002) 321.

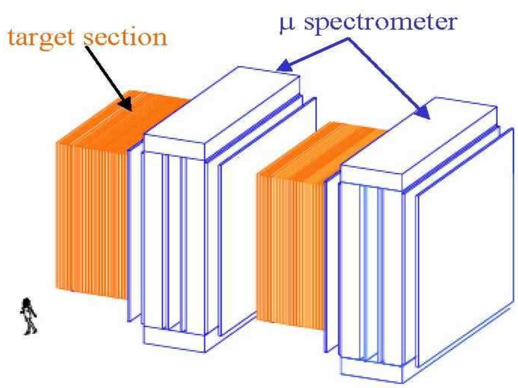
D. Autiero *et al.*, hep-ph/0305185.

- **In the MID it is dumped because of the kinematical cuts.**
- **A detector that could detect the τ decay vertex is needed.**
- **OPERA PROPOSAL for an Emulsion Cloud Chamber ECC with spectrometers. It is possible to think ∼4-5 Kton ECC detector.**

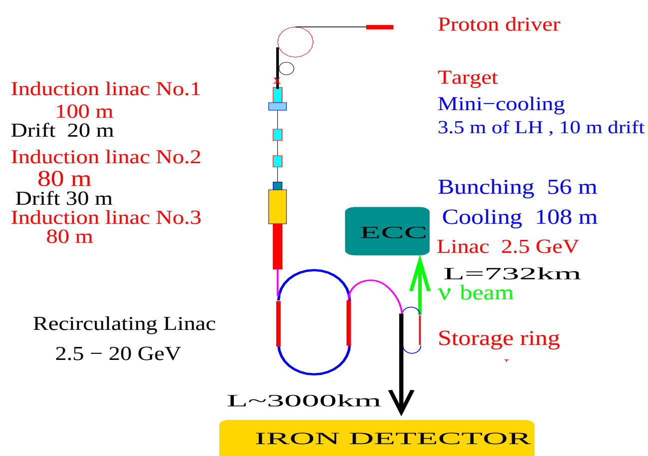
$$\Downarrow$$

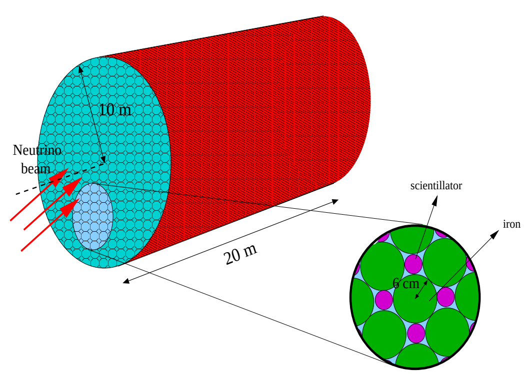
Experience with emulsions and/or ν_τ searches: E531, CHORUS, NOMAD and DONUT.

- **Separation of golden and silver muons.**
- **FOUR ECC bins by maximize the sensitivity of the experiment.**
- **The overall efficiency (including BR) is $\sim 5\%$.**
- **Three dominant sources of backgrounds:**
  1. **Wrong sign μ's from charged-charmed meson decays.**
  2. **Punch-through mesons mimic wrong sign μ's.**
  3. **Right sign μ's whose charge is wrongly identified (the charge MISID is $\sim 0.1 - 0.3\%$.)**



D. Autiero *et al.*, hep-ph/0305185.

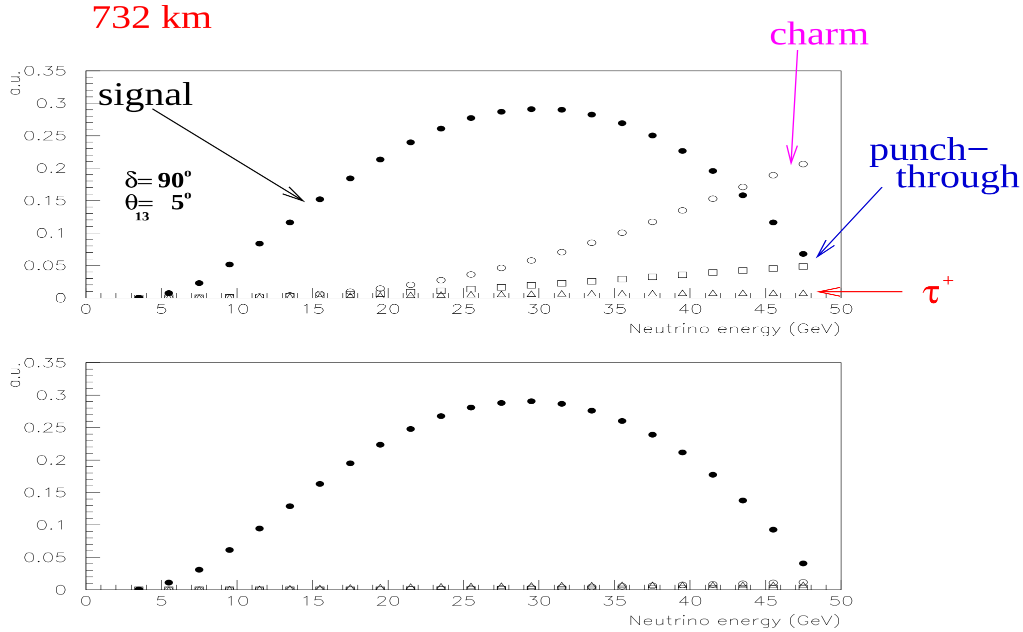




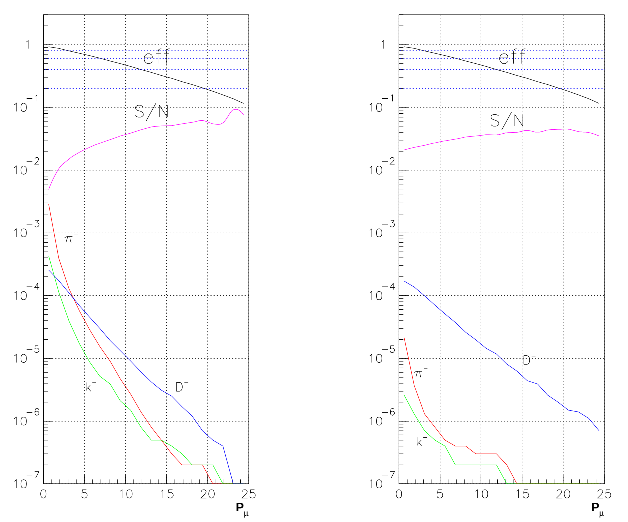
A. Cervera, F. Dydak and J. Gomez Cadenas, Nucl. Instrum. Meth. A **451** (2000).

Signal & backgrounds

Silver channel (D. Autiero *et al.*, hep-ph/0305185.)



Golden channel (A. Cervera *et al.*, Nucl. Phys. B **579** (2000) 17.)



$\bar{\nu}_\mu$- NC $\bar{\nu}_\mu$- CC

1. ***"In the past, systematic errors both on the signal and on the background were not taken into account, regarding the golden channels."***

2. ***"The small expected uncertainties on the remaining oscillation parameters have been also included and we did not find dramatic effects."***

   (J. Burguet-Castell, M. B. Gavela, J. J. Gomez-Cadenas, P. Hernandez and O. M, Nucl. Phys. B **608**, (2001) 301.)

3. ***"A realistic estimate of the systematic error both in the signal and on the background is mandatory in order to have a reliable evaluation of the golden and silver channels synergy."***

Silver channel

Signal Emulsion scanning efficiency and $\frac{\sigma_\tau}{\sigma_\mu} \to \mathcal{O}(15\%)$.

Background $\to \mathcal{O}(10\% - 50\%)$, depending on the source.

Golden channel

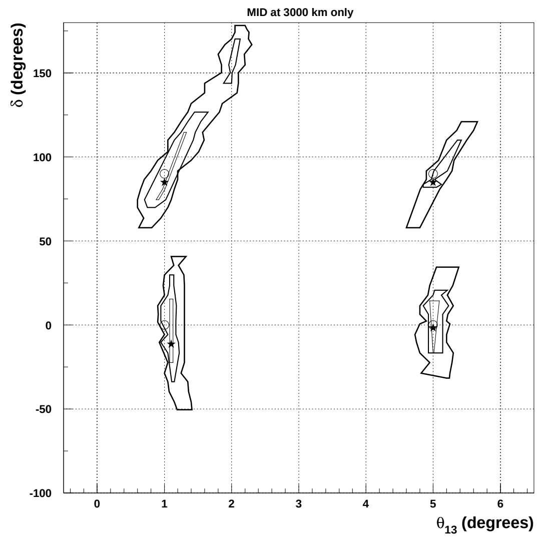
Signal $\to \mathcal{O}(10\%)$.

Background $\to \mathcal{O}(50\%)$, consistent with the *silver* treatment.

(D. Autiero *et al.*, hep-ph/0305185.)

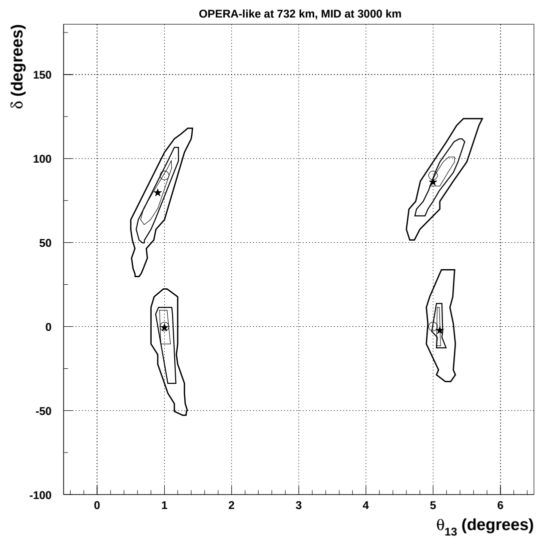
Golden channels at 3000 km, MID.

$\delta = 0°, 90°$, $\theta_{13} = 1°, 5°$.



68.5%, 90% and 99% C. L.

+ silver channel at 732 km, OPERA-like detector.



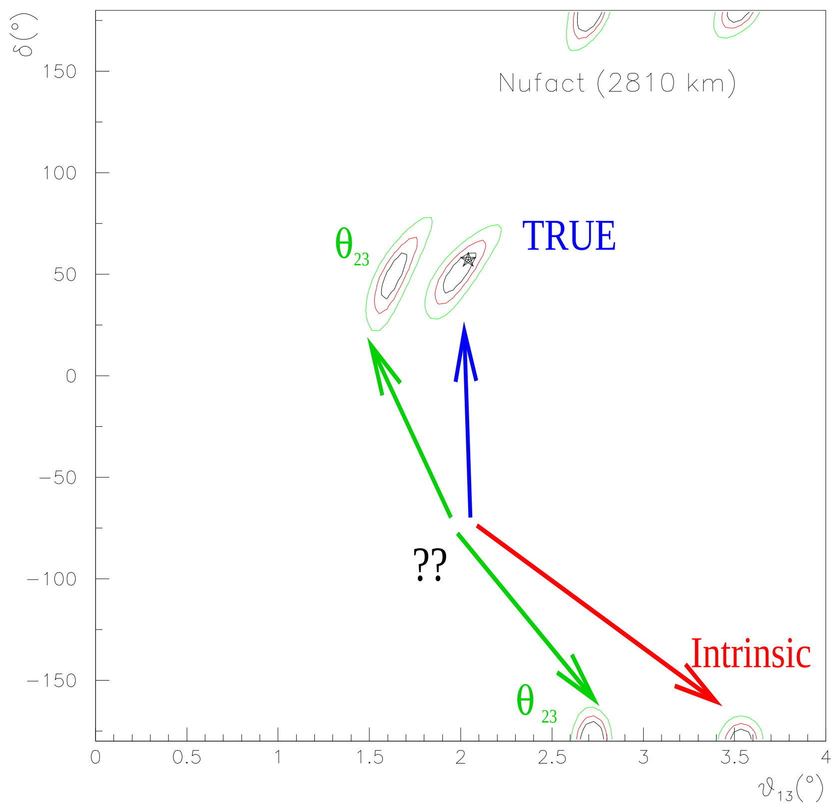
No intrinsic *clones* for $\theta_{13} > 1°$!

(D. Autiero *et al.*, hep-ph/0305185.)

But...more *clones* appear!

Our first example at $\mathcal{O}(3000km)$, and central values:

$\delta = 54°$, $\theta_{13} = 2°$ looks like:



Two additional sources of *clones*:

θ_{23}**- Octant** $\longrightarrow$ $P(\theta'_{13}, \delta', \frac{\pi}{2} - \theta_{23}) = P(\theta_{13}, \delta)$

(G.L. Fogli and E. Lisi, Phys. Rev. **D54** (1996); V. Barger *et al*, Phys. Rev. **D65** (2002).)

Sign-Δm^2_{13} $\longrightarrow$ $P(\theta'_{13}, \delta', -\Delta m^2_{13}) = P(\theta_{13}, \delta)$

(H. Minakata and H. Nunokawa, JHEP **0110** (2001); V. Barger *et al*, Phys. Rev. **D65** (2002).)

- **There exists two types of fake solutions for each ambiguity:**
  1. Solution I: Closer to nature's values (central values) , E/L independent, difficult to overcome.
  2. Solution II: E/L dependent.
- **A dedicated theoretical study of the location of the clones for future neutrino experiments can be found in A. Donini, D. Meloni and S. Rigolin, *"Clone flow analysis for a theory inspired neutrino experiment planning,"* hep-ph/0312072.**
- **Fake solution I for the θ_{23}- Octant ambiguity is very dangerous and can lie far apart from the *true* values.**

$$\Downarrow$$

Second motivation to look for the "silver channel", $\nu_e \longrightarrow \nu_\tau$.

Gorgeous Oscillation Lines DisEntangling Neutrino

&

Solution IntrinsicLones Valuable Elimination Remnants

A. Cervera, A. Donini, M. B. Gavela, J. J. Gomez Cadenas, P. Hernandez, O. M and S. Rigolin, Nucl. Phys. B **579** (2000).

$$P_{\nu_e \nu_\tau (\bar{\nu}_e \bar{\nu}_\tau)} = \longrightarrow s_{23}^2 \, \sin^2 2\theta_{13} \, \sin^2 \frac{\Delta m_{13}^2 L}{4E}$$

$$+ \longrightarrow c_{23}^2 \, \sin^2 2\theta_{12} \, \sin^2 \frac{\Delta m_{12}^2 L}{4E}$$

$$- \, \tilde{J} \, \cos\left(\pm\delta - \frac{\Delta m_{13}^2 L}{4E} \right) \frac{\Delta m_{12}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E}$$

Probabilities for golden and silver channels also differ by the interchange $\theta_{23} \rightarrow \frac{\pi}{2} - \theta_{23}$.

$\theta_{23},\ \pi/2-\theta_{23}$ *Clones* (I)

In vacuum approximation:

golden θ_{13} *large*

$$\begin{cases} \sin\delta' = \cot\theta_{23}\ \sin\delta, \\ \theta'_{13} \simeq \tan\theta_{23}\ \theta_{13} \\ +\dfrac{\sin 2\theta_{12}\frac{\Delta m^2_{12}L}{4E}}{2\sin\left(\frac{\Delta m^2_{13}L}{4E}\right)}\left(\cos\left(\delta-\frac{\Delta m^2_{13}L}{4E}\right)-\tan\theta_{23}\cos\left(\delta'-\frac{\Delta m^2_{13}L}{4E}\right)\right). \end{cases}$$

silver θ_{13} *large*

$$\begin{cases} \sin\delta' = \tan\theta_{23}\ \sin\delta, \\ \theta'_{13} \simeq \cot\theta_{23}\ \theta_{13} \\ -\dfrac{\sin 2\theta_{12}\frac{\Delta m^2_{12}L}{4E}}{2\sin\left(\frac{\Delta m^2_{13}L}{4E}\right)}\left(\cos\left(\delta-\frac{\Delta m^2_{13}L}{4E}\right)-\tan\theta_{23}\cos\left(\delta'-\frac{\Delta m^2_{13}L}{4E}\right)\right). \end{cases}$$

The shifts $\theta'_{13}-\theta_{13}$ have different sign.

J. Burguet-Castell, M. B. Gavela, J. J. Gomez-Cadenas, P. Hernandez and O. M, Nucl. Phys. B **646**, (2002) 301.

$\theta_{23},\ \pi/2-\theta_{23}$ *Clones* (II)

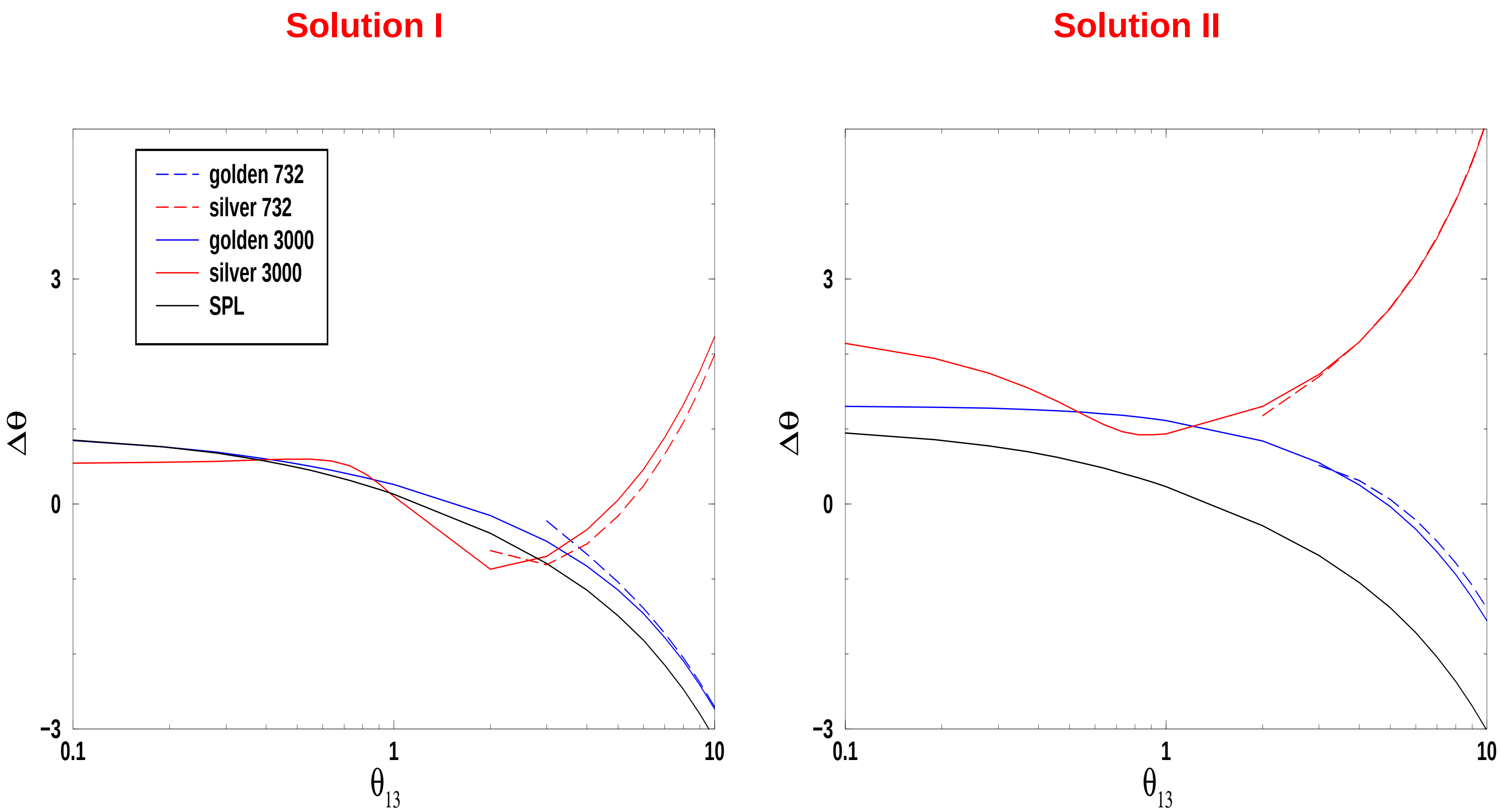
$$\theta_{13}\to 0^\circ \begin{cases} 1 \text{ golden and silver} \begin{cases} \delta' \sim 0 \\ \theta'_{13} \sim \sin 2\theta_{12}\frac{\Delta m^2_{12}L}{4E}\left|(\tan\theta_{23}-1)\csc\frac{\Delta m^2_{13}L}{2E}\right|. \end{cases} \\ 2 \begin{cases} \text{golden } \delta' \sim \pi \\ \text{silver } \delta' \sim 0 \\ \theta'_{13} \sim \sin 2\theta_{12}\frac{\Delta m^2_{12}L}{4E}\left(\left|\cot\frac{\Delta m^2_{13}L}{4E}\right| \pm_{\text{S}}^{\text{G}} (\tan\theta_{23}-1)\cot\frac{\Delta m^2_{13}L}{2E}\right). \end{cases} \end{cases}$$

The condition for the existence of solutions is also different:

$$\text{No clones if} \begin{cases} \text{golden } \tan^2\theta_{23} < \dfrac{1}{\sin^2\left(\frac{\Delta m^2_{13}L}{4E}\right)}. \\ \text{silver } \cot^2\theta_{23} < \dfrac{1}{\sin^2\left(\frac{\Delta m^2_{13}L}{4E}\right)} \end{cases}$$

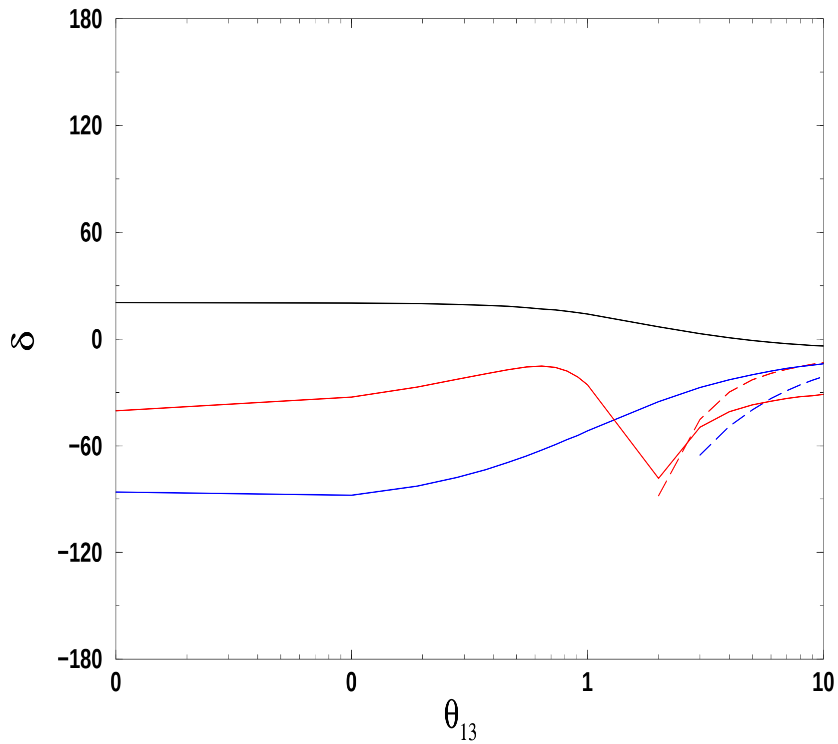
J. Burguet-Castell, M. B. Gavela, J. J. Gomez-Cadenas, P. Hernandez and O. M, Nucl. Phys. B **646**, 301 (2002).

$\theta_{23},\ \pi/2 - \theta_{23}$ *Clones* (III): $\theta'_{13} - \theta_{13}$ for $\delta = 0°$

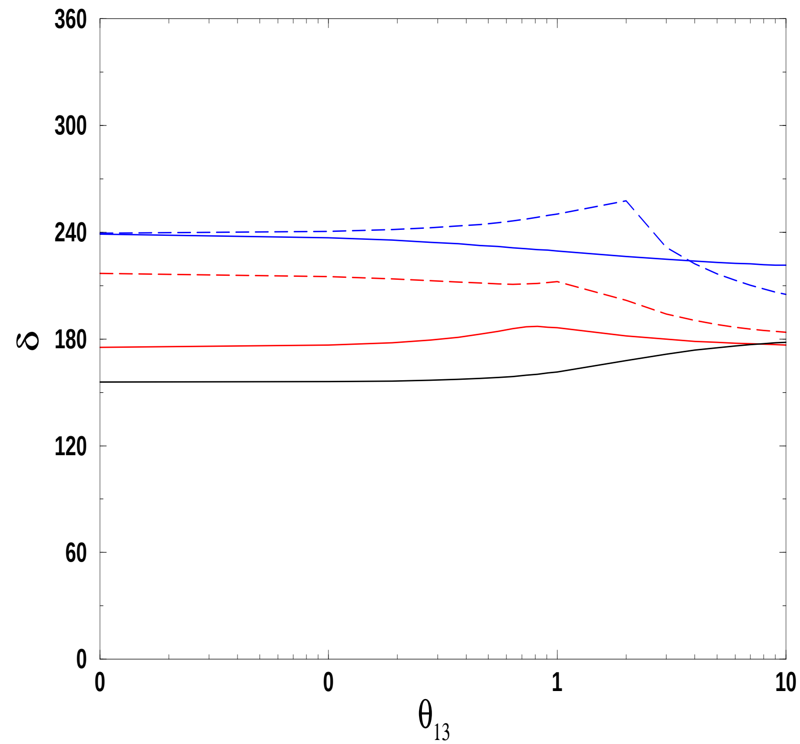


$\theta_{23},\ \pi/2-\theta_{23}$ *Clones* (IV): δ' for $\delta = 0°$

Solution I

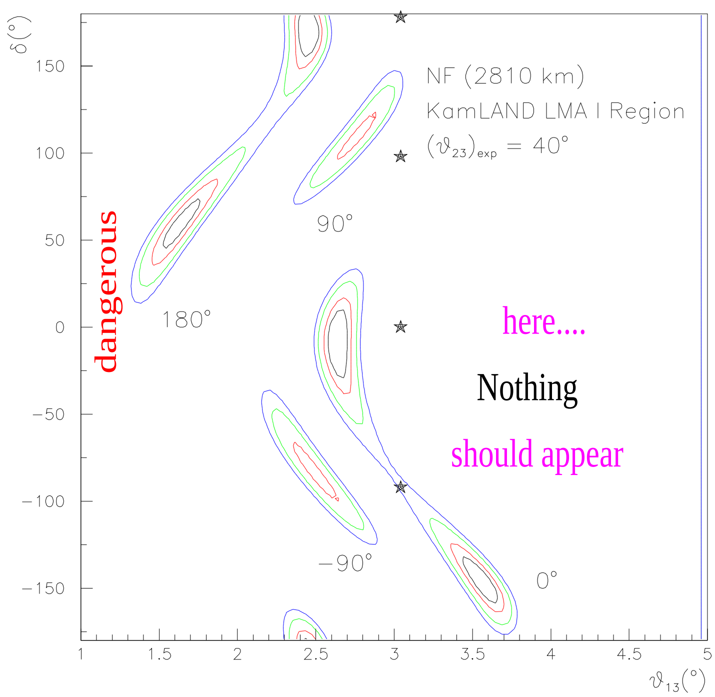


Solution II



First stage of a detailed study under preparation (A. Donini *et al.*):

- **We have considered the impact of the combination of golden (40 kton MID and L=2810 km) and silver (4 Kton ECC and L=732 km) channels.**
- **2 years running π^+'s, 10 years π^-'s.**
- **By using ONLY golden muons (MID, L=2810 km) and central values: $\delta = 180°, -90°, 0°$ and $90°$, $\theta_{13} = 3°$.**



(O. Mena, hep-ph/0305146.)

The combination get rid of the θ_{23} clones!

Conclusions

- **ν oscillation data $\longrightarrow$ NP $\&$ understanding of flavor puzzle.**
- **Measurement of Leptonic CP violation.**

PUZZLING OUT LEPTONIC SECTOR!

$\Downarrow$

PRECISION EXPERIMENTS

δ ? θ_{13} ? $\longrightarrow$ Neutrino Factory!

- **Our setup: 10^{21} μ^+ AND μ^- of 50 GeV.**

"golden": $\nu_e \longrightarrow \nu_\mu$ ($\bar{\nu}_e \longrightarrow \bar{\nu}_\mu$), 40 kton MID, $L \sim 3000$ km.

"A good signal with high statistics and low background".

+

"silver": $\nu_e \longrightarrow \nu_\tau$ ($\bar{\nu}_e \longrightarrow \bar{\nu}_\tau$), 4 kton ECC, $L = 732$ km.

"A difficult-to-signal with low statistics, but crucial to solve the clones".

- **INTRINSIC DEGENERACIES disappear down to $\theta_{13} \sim 1^\circ$.**
- **At small θ_{13} ($\theta_{13} < 1^\circ$ (preliminary!), the θ_{23}-octant (40° or 50°?) remains as an ambiguity, but does not interfere with the determination of θ_{13} and δ.**

SUPER BEAMS $\&$ NEUTRINO FACTORIES (golden+silver)

running simultaneously!

Improvements (+ βBeams, Future reactors)

....work in progress