Combining GOLDEN and SILVER muons to resolve ambiguities

Outline

- The source of the (θ_{13}, δ) ambiguity.
- Silver muons:
  - ▷ ENE curves for $\nu_e \to \nu_\tau$
  - ▷ Using an emulsion detector for $\nu_e \to \nu_\tau$
- Combining $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$:
  Two iron vs. One iron and one emulsion:
  - ▷ the ideal case;
  - ▷ the real case;
  - ▷ how to improve?
- Conclusions.

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The Golden Channel at the Neutrino Factory

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

The oscillation probability is

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

with

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

$(+$ neutrinos, $-$ antineutrinos$)$

Equal-Number-of-Events Curves

The number of GOLDEN muon events is:

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

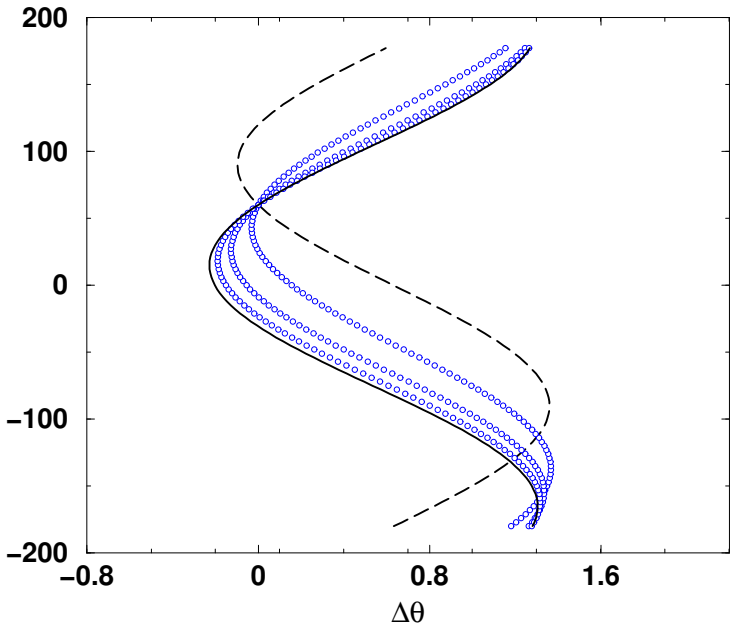
with i a given energy bin.

By changing (θ_{13},δ) accordingly,
we draw ENE curves in the (θ_{13},δ) plane:

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

$L = 3000$ Km

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



How to draw ENE curves

We get an IMPLICIT equation for δ as a function of θ_{13} and of the input pair $(\bar{\theta}_{13}, \bar{\delta})$

$$F_i(\delta) = G_i(\theta_{13}, \bar{\theta}_{13}, \bar{\delta})$$

with

$$F_i(\delta) = \cos\delta \pm \left(\frac{I^i_{Y_s}}{I^i_{Y_c}}\right) \sin\delta \,,$$

$$G_i(\theta_{13}, \bar{\theta}_{13}, \bar{\delta}) = \left(\frac{I^i_X}{I^i_{Y_c}}\right) f(\theta_{13}, \bar{\theta}_{13}) + F_i(\bar{\delta}) g(\theta_{13}, \bar{\theta}_{13})$$

where

$$I_{\hat{O}} = \sigma \otimes \hat{O} \otimes \Phi$$

and

$$\begin{cases} f(\theta_{13}, \bar{\theta}_{13}) = \frac{\sin^2(2\bar{\theta}_{13}) - \sin^2(2\theta_{13})}{\cos\theta_{13}\sin(2\theta_{13})} \,, \\ g(\theta_{13}, \bar{\theta}_{13}) = \frac{\cos\bar{\theta}_{13}\sin(2\bar{\theta}_{13})}{\cos\theta_{13}\sin(2\theta_{13})} \,. \end{cases}$$

A Gedanken Experiment

Input: $\bar{\theta}_{13}$ and $\bar{\delta}$

$\Downarrow$

Golden Muons at fixed baseline L

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

for five energy bins, $i = 1, \ldots 5$

$\Downarrow$

"Experimental" Data Generation

$$n^i_\pm = \text{Smear}\left[\epsilon N + B\right]^i_\pm$$

$\Downarrow$

Fit to the theoretical probability

$$\chi^2 = \sum_\pm \sum_i \left(\frac{n^i_\pm - N^i_\pm}{\delta n^i_\pm} \right)^2$$

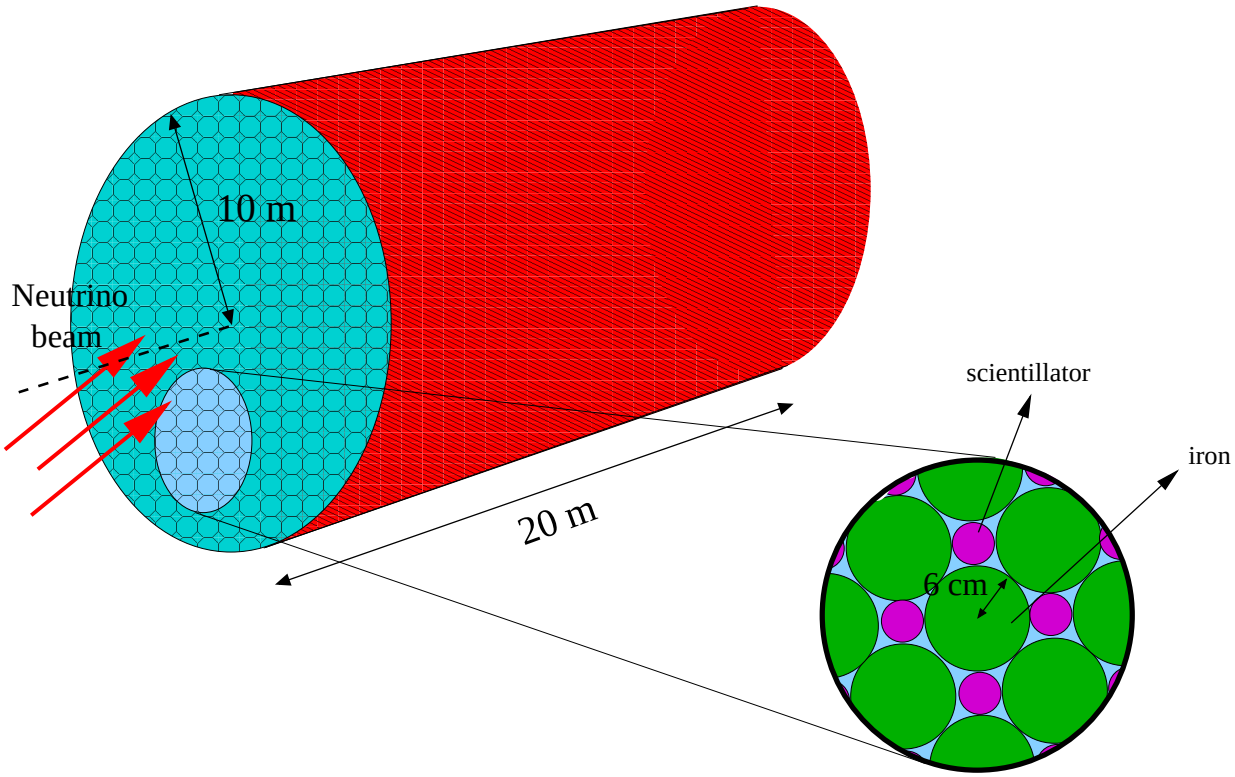
or

$$\chi^2 = -2 \sum_\pm \sum_i \left[\left(n^i_\pm - N^i_\pm\right) - n^i_\pm \log\left(\frac{n^i_\pm}{N^i_\pm}\right) \right]$$

$\Downarrow$

Output: $\bar{\theta}_{13}$ and $\bar{\delta}$?

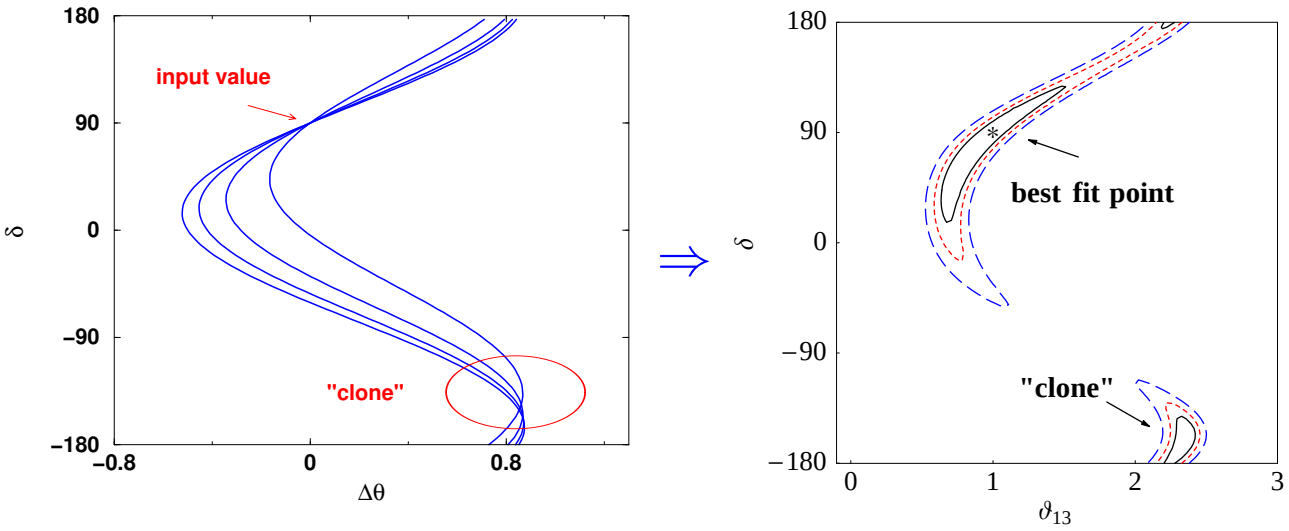
A 40 Kton Magnetized Iron Detector



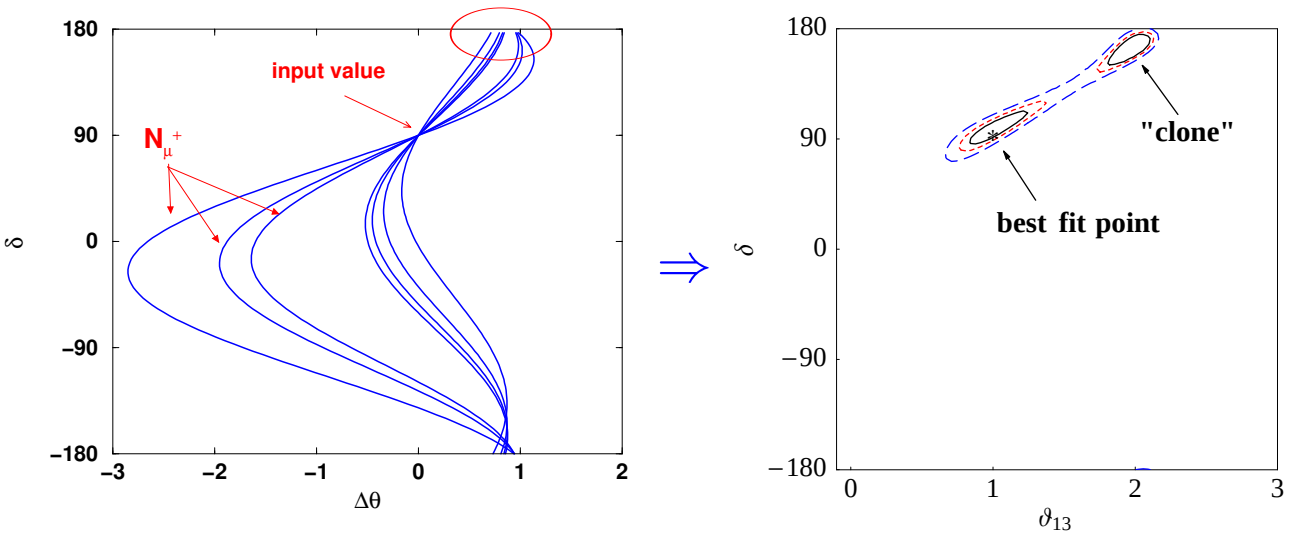
- good μ charge ID:
  (10^{-6} misidentification claimed)
- energy resolution: $\Delta E_\nu = 10$ GeV
  (an ICARUS-type detector is better)
- (relatively) cheap and tested
- known background $B(E_\nu)$ and efficiency $\epsilon\,(E_\nu)$

Results for golden muons at $L = 3000$ Km

Five years of data taking: one polarity only
(μ^+ in the storage ring)



Ten years of data taking: two polarities
(μ^+ and μ^- in the storage ring)



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

Caveat

- In what follows, we restrict ourselves to the study of the (θ_{13}, δ) ambiguity.
- In particular,
  - $\theta_{23} = 45°$: no $(\theta_{23}, \pi/2 - \theta_{23})$ ambiguity.
  - The sign of Δ_{atm} has been kept fixed: we performed simulations for both signs, with similar results; (in the following, $\Delta_{atm} \geq 0$)
- Next step: we plan to study the sign and (θ_{13}, δ) ambiguities at the same time.

The other parameters:

- Solar sector:
  $\theta_{12} = 33°$,
  $\Delta m^2_{\odot} = 1.0 \times 10^{-4}$ eV^2
- Atmospheric sector:
  $\theta_{23} = 45°$,
  $\Delta m^2_{atm} = 2.9 \times 10^{-3}$ eV^2
- Matter parameter: $A = 1.1 \times 10^{-4}$ eV^2/GeV

The Silver Channel at the Neutrino Factory

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

The oscillation probability is

$$P^{\pm}_{e\tau} = X^{\tau}_{\pm} \sin^2(2\,\theta_{13}) - Y_{\pm} \cos\left(\delta \mp \frac{\Delta_{atm} L}{2}\right) \cos\theta_{13} \sin(2\,\theta_{13}) + Z^{\tau} + \ldots$$

with

$$\begin{cases} X^{\tau}_{\pm} &= \Delta^2_{atm} \times (c^2_{23}/s^2_{23}) f^{\pm}_X(\theta_{23}, A, L) \\ Y_{\pm} &= \Delta_{sun} \times \Delta_{atm} \times f^{\pm}_Y(\theta_{12}, \theta_{23}, A, L) \\ Z^{\tau} &= \Delta^2_{sun} \times (s^2_{23}/c^2_{23}) f_Z(\theta_{12}, \theta_{23}, A, L) \end{cases}$$

($+$ neutrinos, $-$ antineutrinos)

Silver ENE Curves

The number of SILVER muon events is:

$$N^i_{\mu^-}(\bar{\theta}_{13}, \bar{\delta}) = BR\,(\tau \to \mu) \times$$

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

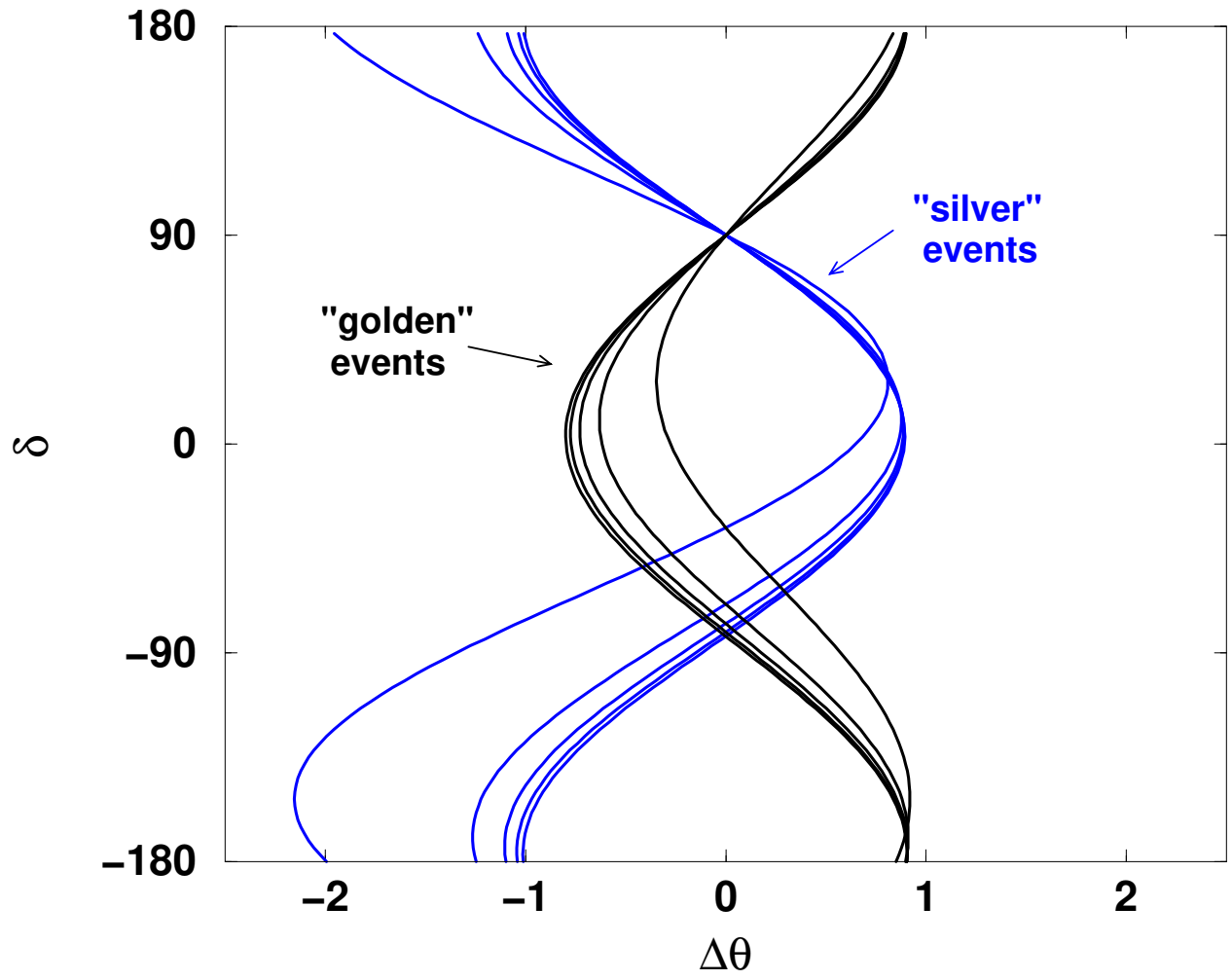
with i a given energy bin.

Notice:

- The σ_{ν_τ} cross-section: a strong depletion of the signal with respect to golden muons
- The dN_{μ^-} distribution :
  - look for the τ decay vertex or
  - use the different kinematical distribution

  to distinguish golden from silver muon events.

Comparison of ENE curves



Baseline: $L = 732$ Km

$$\begin{cases} \bar{\theta}_{13} &= 1^\circ \\ \bar{\delta} &= 90^\circ \end{cases}$$

Using a Lead-Emulsion Detector (1)

In the MAGNETIZED IRON DETECTOR, the main background to GOLDEN MUONS comes from charmed mesons decay.

Unfortunately,

- the kinematical cuts needed to decrease the background cancel the SILVER MUONS SIGNAL, also.
- we cannot use the different energy distribution for GOLDEN and SILVER muons.

We need a detector that could detect the τ decay vertex (or a high granularity magnetized detector?).

$$\Downarrow$$

We follow the OPERA proposal for a 2 Kton Lead-Emulsion detector with spectrometers.

Using a Lead-Emulsion Detector (2)

Advantages:

- ▷ Good vertex identification.
- ▷ OPERA operational in 2006
  (fixed baseline $\Rightarrow$ $L = 732$ Km).
- ▷ Known technology
  $\Rightarrow$ foreseeable improvements:
  - Lead-emulsion mass increase?
  - A 10^{-3} charge MISID claimed.
    Can we do better?

▷ If you think that a Neutrino Factory beam will produce too many events to be scanned:

for $\bar{\theta}_{13} = 5^\circ, \bar{\delta} = 60^\circ$,

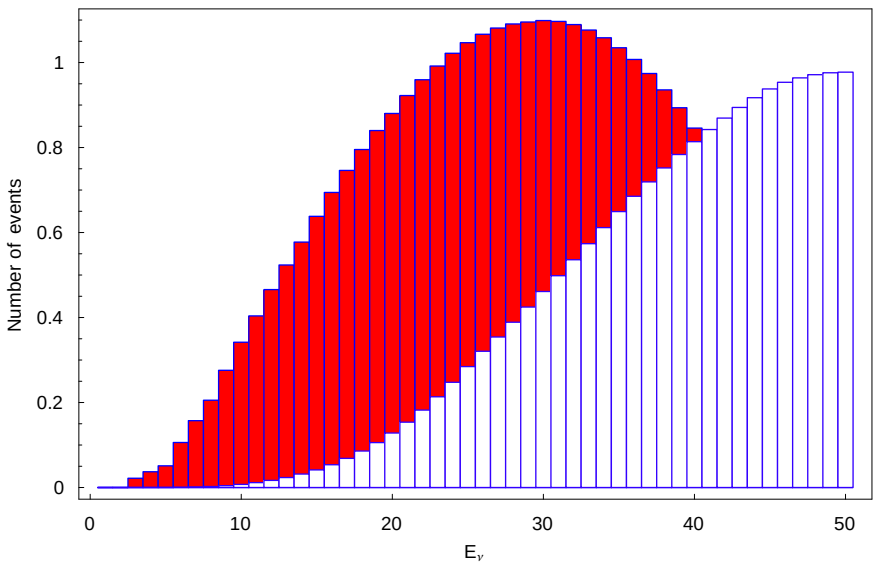
$$\begin{cases} N_{golden} & \sim & 700 \\ N_{silver} & \sim & 30 \end{cases}$$

$\Rightarrow$ compatible with PRESENT scanning power.
By 2010-2020 we can surely do better....

Vertex identification

Vertex identification allows:

- ▷ Separation of GOLDEN and SILVER muons;
- ▷ Separation of GOLDEN muons and Backgrd;
- ▷ Use of the SILVER MUONS energy distribution to increase the S/B ratio.



In the lead-emulsion detector:

- GOLDEN muons backgrd (B_{golden}) from charge misidentification;
- SILVER muons backgrd (B_{silver}) from charge mesons decay.

The Factory-detectors set-up

We consider a Neutrino Factory with:

- 2×10^{20} useful muons/(year)/(straight section)
- $\bar{E}_\mu = 50$ GeV muons of two polarities
- five years of data taking for both polarities
- two baselines: $L = 732$ and $L = 3000$ Km

We compare two Factory-Detectors combinations:

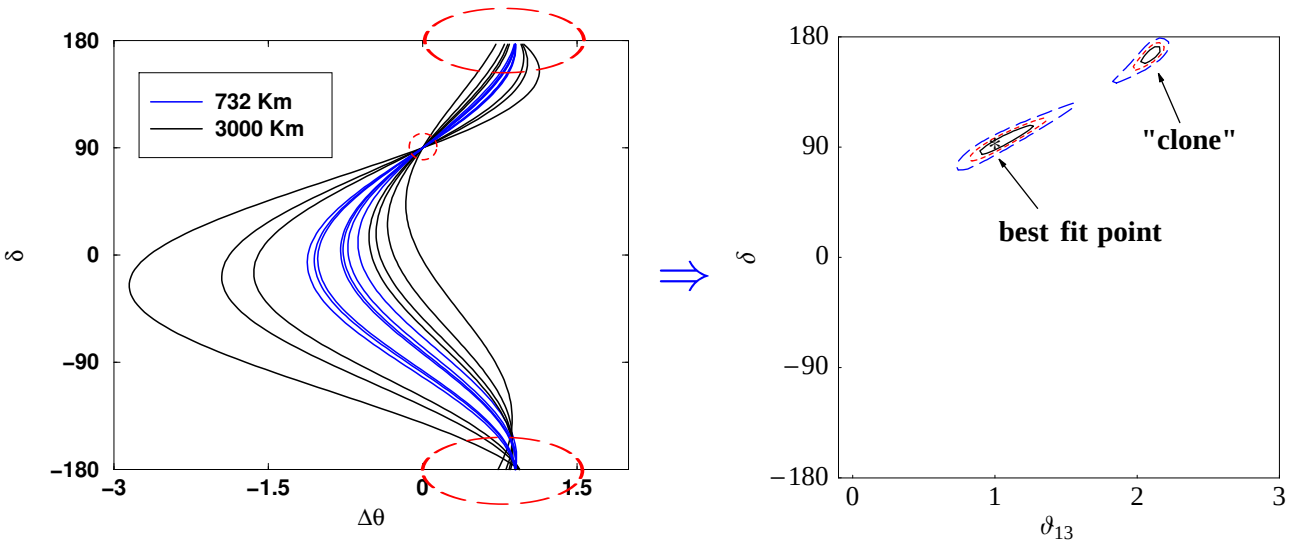
- (A) two 40 Kton iron detectors
  at $L = 732$ and $L = 3000$ Km
- (B) one 40 Kton iron detector at $L = 3000$ and
  one 2 Kton emulsion detector at $L = 732$ Km

Both detectors with realistic estimates of efficiency and background for the different signals:

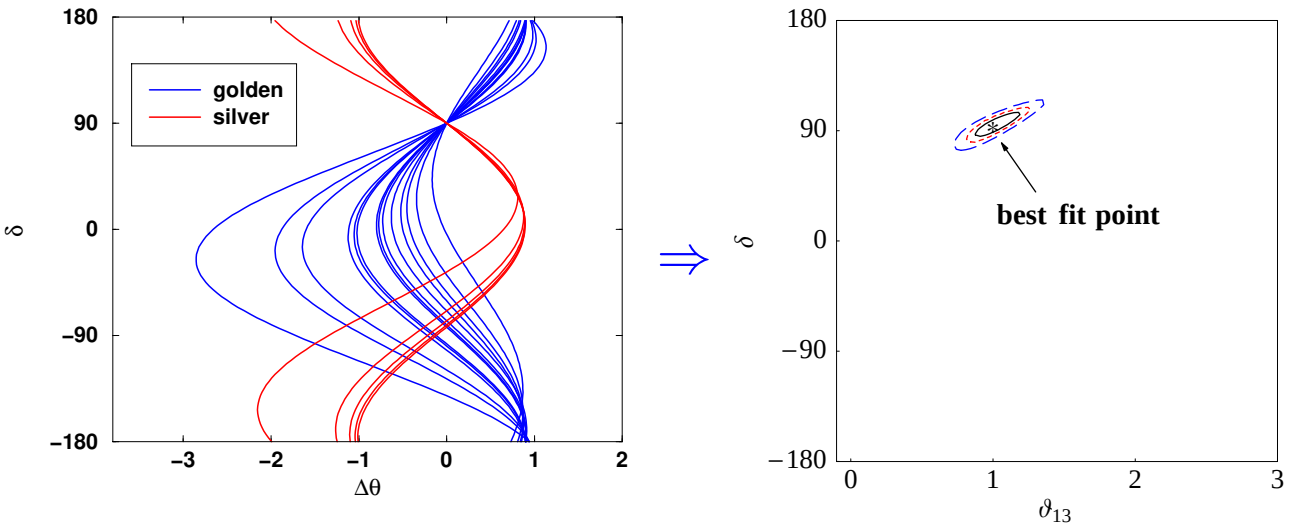
- iron detector: golden muons
- emulsion detector: golden and silver muons

Using golden and silver muons

Setup A: two iron detectors and two baselines (golden muons only)



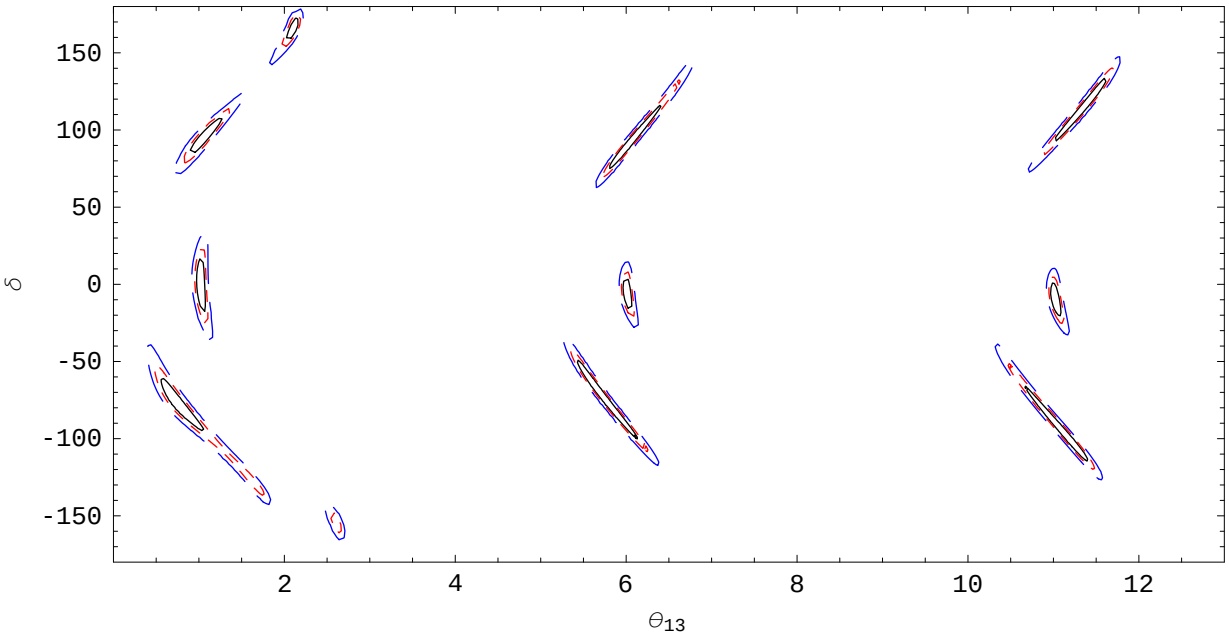
Setup B: one iron and one emulsion detectors (golden and silver muons; IDEAL emulsion detector)



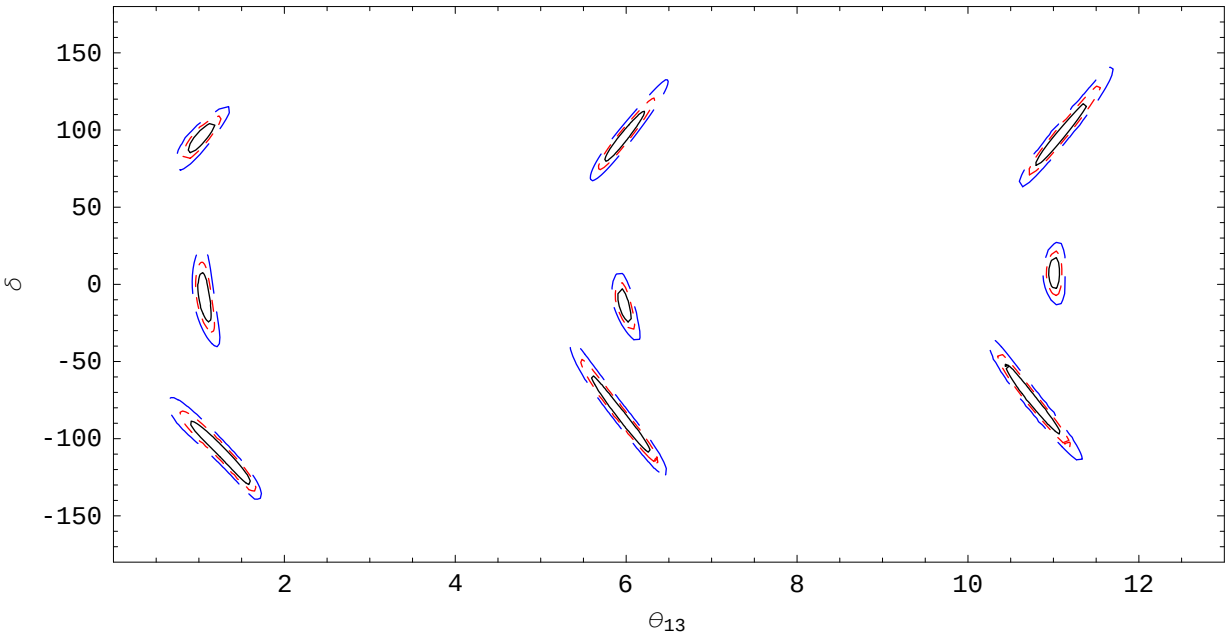
Input parameters: $\bar{\theta}_{13} = 1°, \bar{\delta} = 90°$

The ideal case

Setup A: two iron detectors and two baselines (golden muons only)

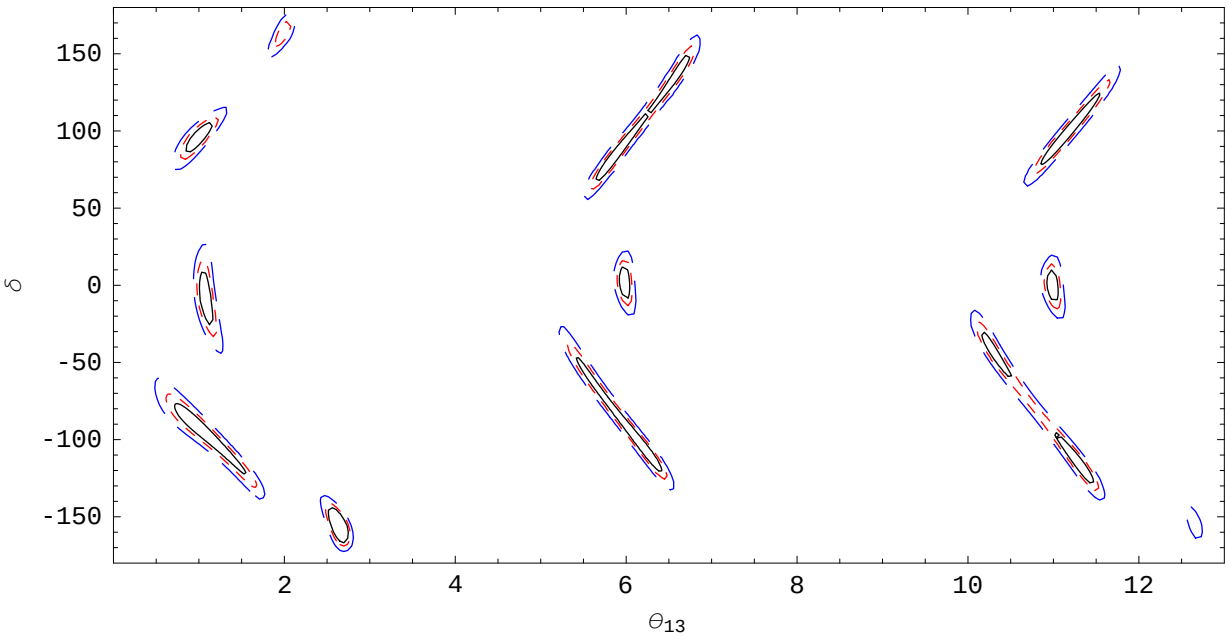


Setup B: one iron and one emulsion detectors (golden and silver muons; IDEAL emulsion detector)

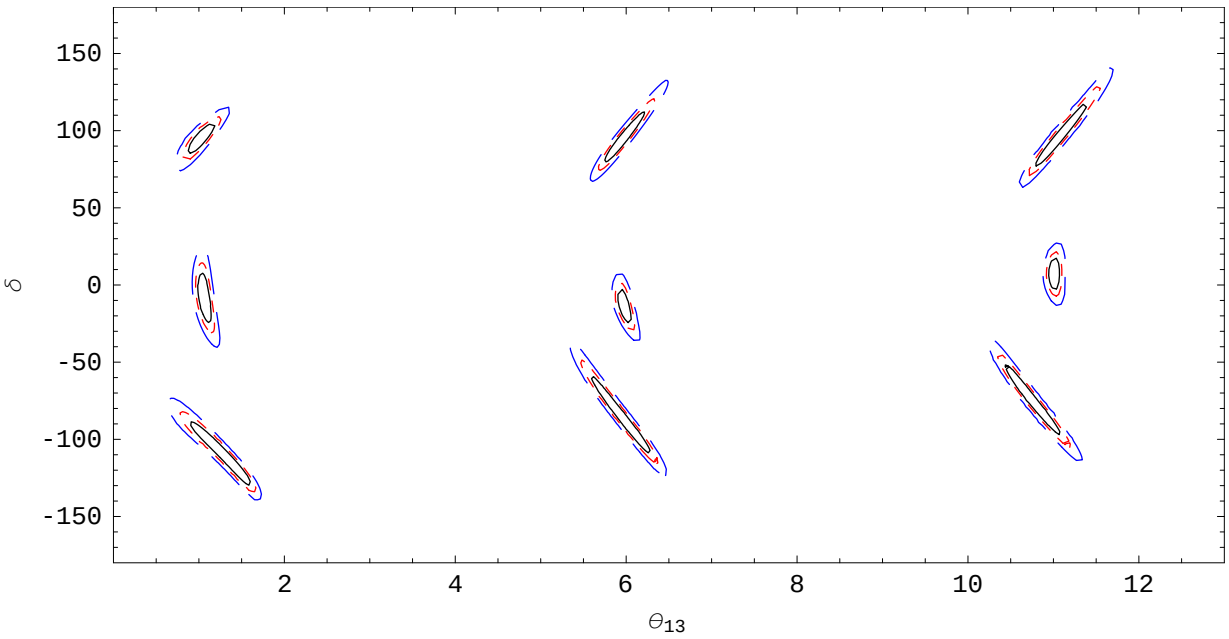


Are silver muons important?

Setup B: one iron and one emulsion detectors
(golden muons ONLY; IDEAL emulsion detector)

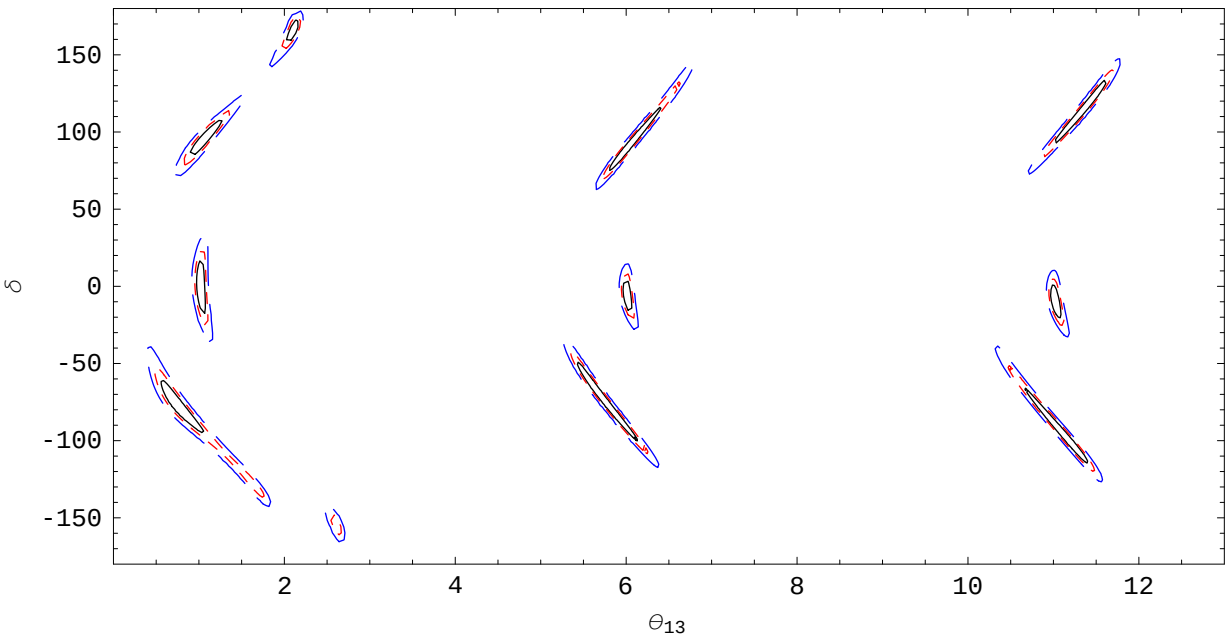


Setup B: one iron and one emulsion detectors
(golden and silver muons; IDEAL emulsion detector)

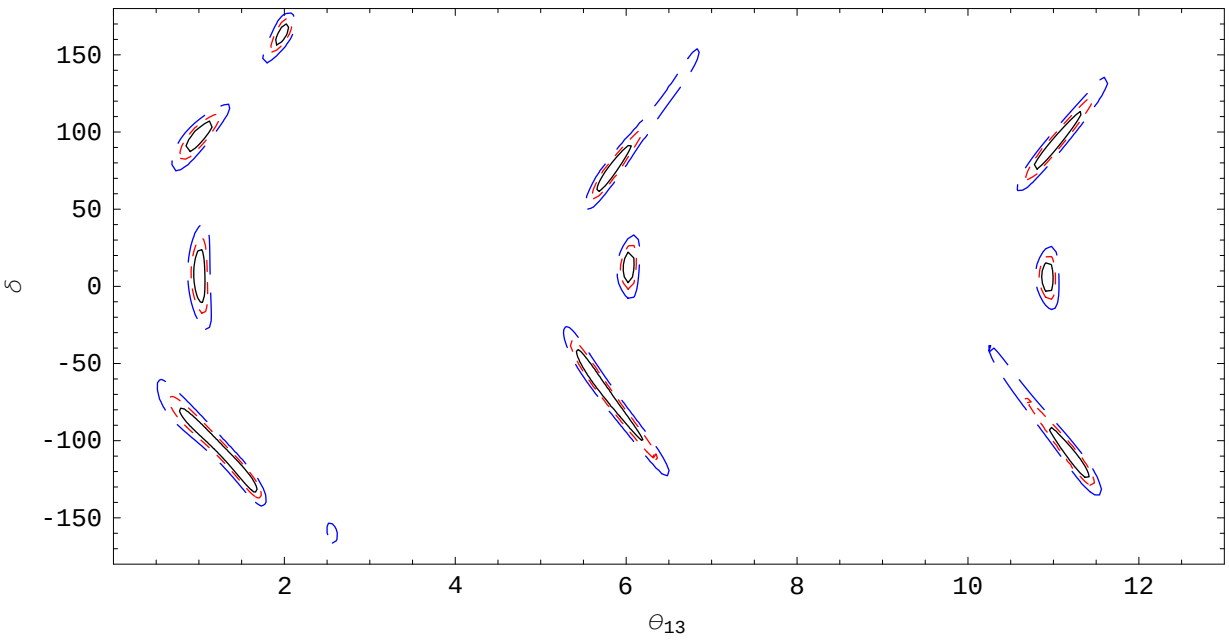


The real case

Setup A: two iron detectors and two baselines (golden muons only)



Setup B: one iron and one emulsion detectors (golden and silver muons; REAL emulsion detector)



How to improve the detector?

Mass (Kton)	B_{silver}	B_{golden}	Clone regions	$\delta_{min}, \delta_{max}$ at 99 % C.L.
2	1.0	10^{-3}	At 68 %	-
	0.8	10^{-3}	At 68 %	-
	1.0	10^{-4}	At 68 %	-
	0.8	10^{-4}	At 90 %	-
3	1.0	10^{-3}	At 99 %	-
	0.8	10^{-3}	At 99 %	-
	1.0	10^{-4}	No	50° - 100°
	0.8	10^{-4}	No	50° - 110°
4	1.0	10^{-3}	No	55° - 105°
	0.8	10^{-3}	No	55° - 105°
	1.0	10^{-4}	No	60° - 110°
	0.8	10^{-4}	No	70° - 110°

- Clone regions disappear increasing the emulsion mass
- Better muon charge ID shifts the 99 % allowed region

Conclusions

▷ $\nu_e \to \nu_\mu$ is the golden channel at the Neutrino Factory: a good signal with high statistics and low background.

▷ $\nu_e \to \nu_\tau$ is the silver channel at the Neutrino Factory: a difficult-to-see signal with low statistics. However, it can be crucial to solve the (θ_{13}, δ) ambiguity and to reduce the error on δ.

- We show that an OPERA-like small (2 Kton) lead-emulsion detector can take full advantage of the silver channel.
- The "one large (40 Kton) iron detector at $L = 3000$ Km and one small (2 Kton) lead-emulsion detector at $L = 732$ Km" combination (golden and silver muons) is competitive with the "two large iron detectors at $L = 732$ and $L = 3000$ Km" one (golden muons only).
- An increase in the emulsion detector mass (from 2 to 4 Kton) could in principle solve the (θ_{13}, δ) ambiguity for $\theta_{13} \geq 1^\circ$.