The $\nu_e \to \nu_\tau$ channel as a tool to solve ambiguities

Outline

- The source of the (θ_{13}, δ) ambiguity
  definition of ENE curves:
  - ▷ application to the $\nu_e \to \nu_\mu$ channel
  - ▷ application to the $\nu_e \to \nu_\tau$ channel:
    using an emulsion detector
- 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

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

The oscillation probability is

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

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 (ENE) Curves

The number of GOLDEN muon events is:

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

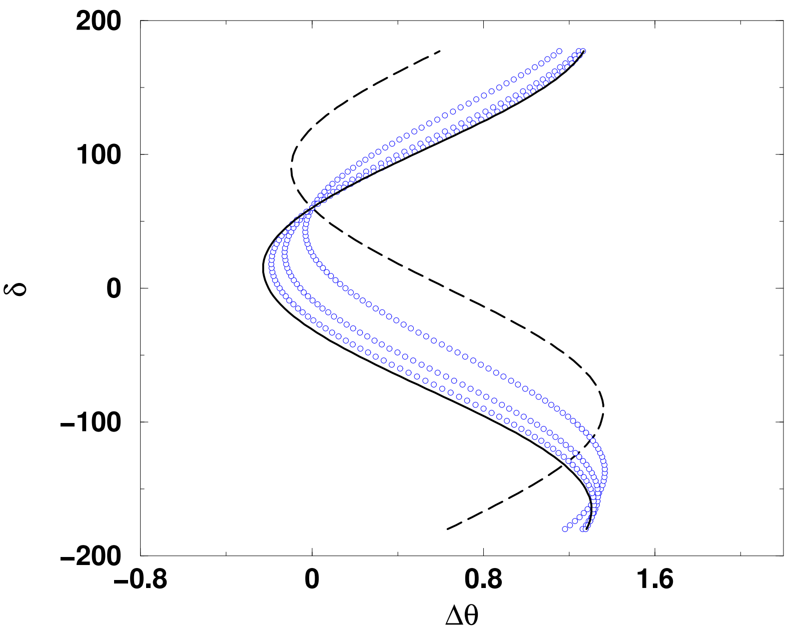
with i a given neutrino energy bin.

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

$$\begin{cases} \bar\theta_{13} & = & 5^\circ \\ \bar\delta & = & 60^\circ \end{cases}$$

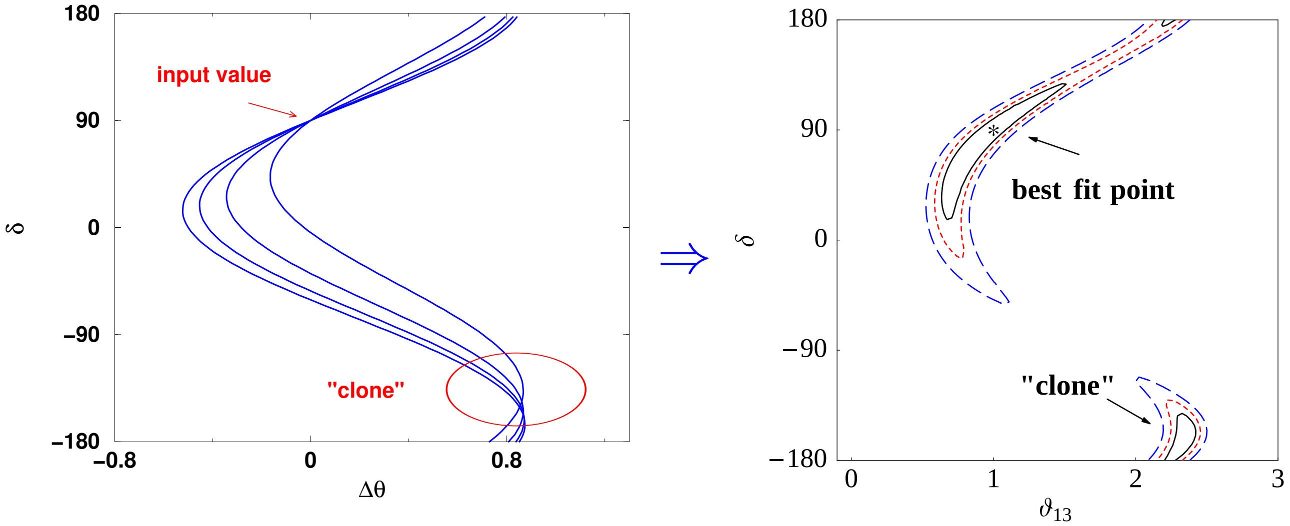


$\Delta\theta =$ shift of θ with respect to the input value

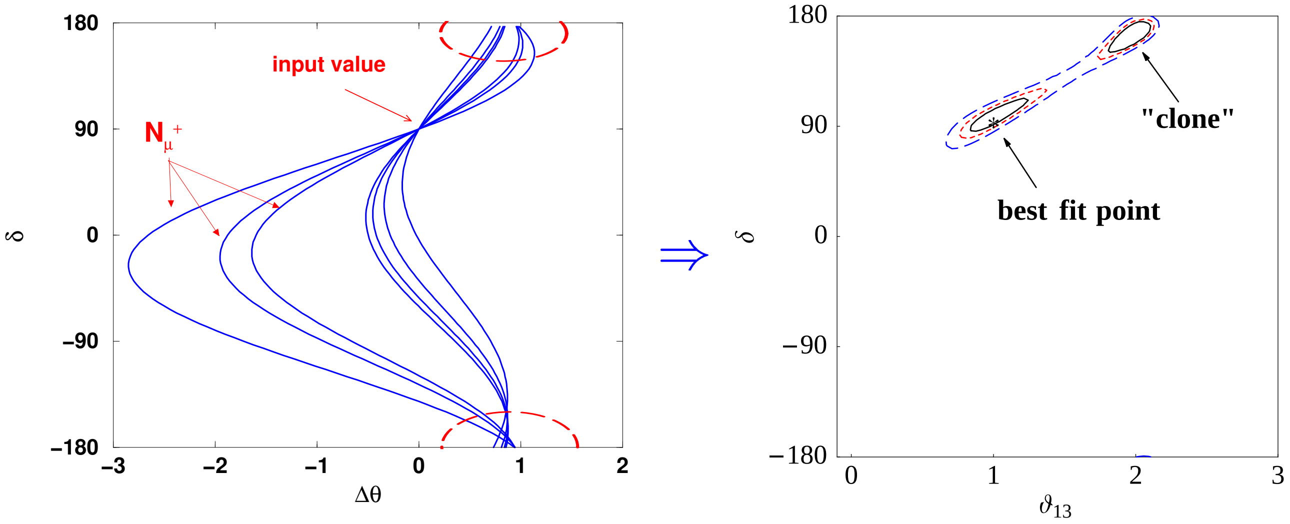
Results for golden muons at $L = 3000$ Km

Iron detector

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: $\bar{\theta}_{13} = 1^\circ, \bar{\delta} = 90^\circ$

The Silver Channel at the Neutrino Factory

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

The oscillation probability is

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

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)

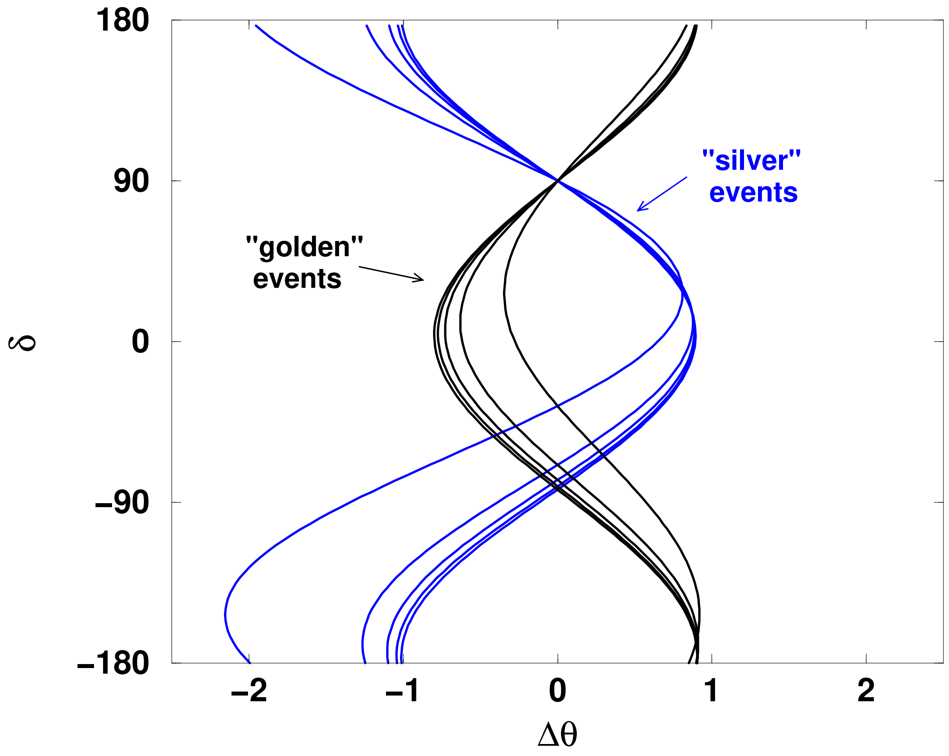
Silver ENE Curves

The number of SILVER muon events is:

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

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

with i a given energy bin



Baseline: $L = 732$ Km

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

In the MAGNETIZED IRON DETECTOR, the SILVER MUONS SIGNAL is dumped because of the kinematical cuts needed to decrease the background

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

$\Downarrow$

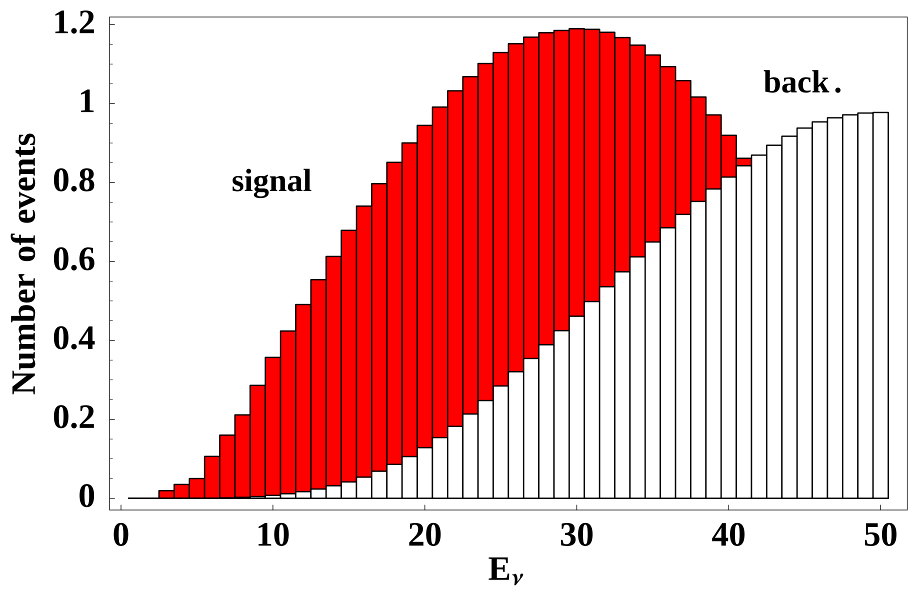
We follow the OPERA proposal for a 2 Kton Lead-Emulsion detector with spectrometers.

Advantages:

- ▷ Good vertex identification which allows:
- – separation of GOLDEN and SILVER muons
- – separation of GOLDEN muons and Backgrd
- ▷ OPERA operational in 2006
  $\Rightarrow$ foreseeable improvements:
  - – Lead-emulsion mass increase?
  - – A 10^{-3} charge MISID claimed.
    Can we do better?

Background in the lead-emulsion detector

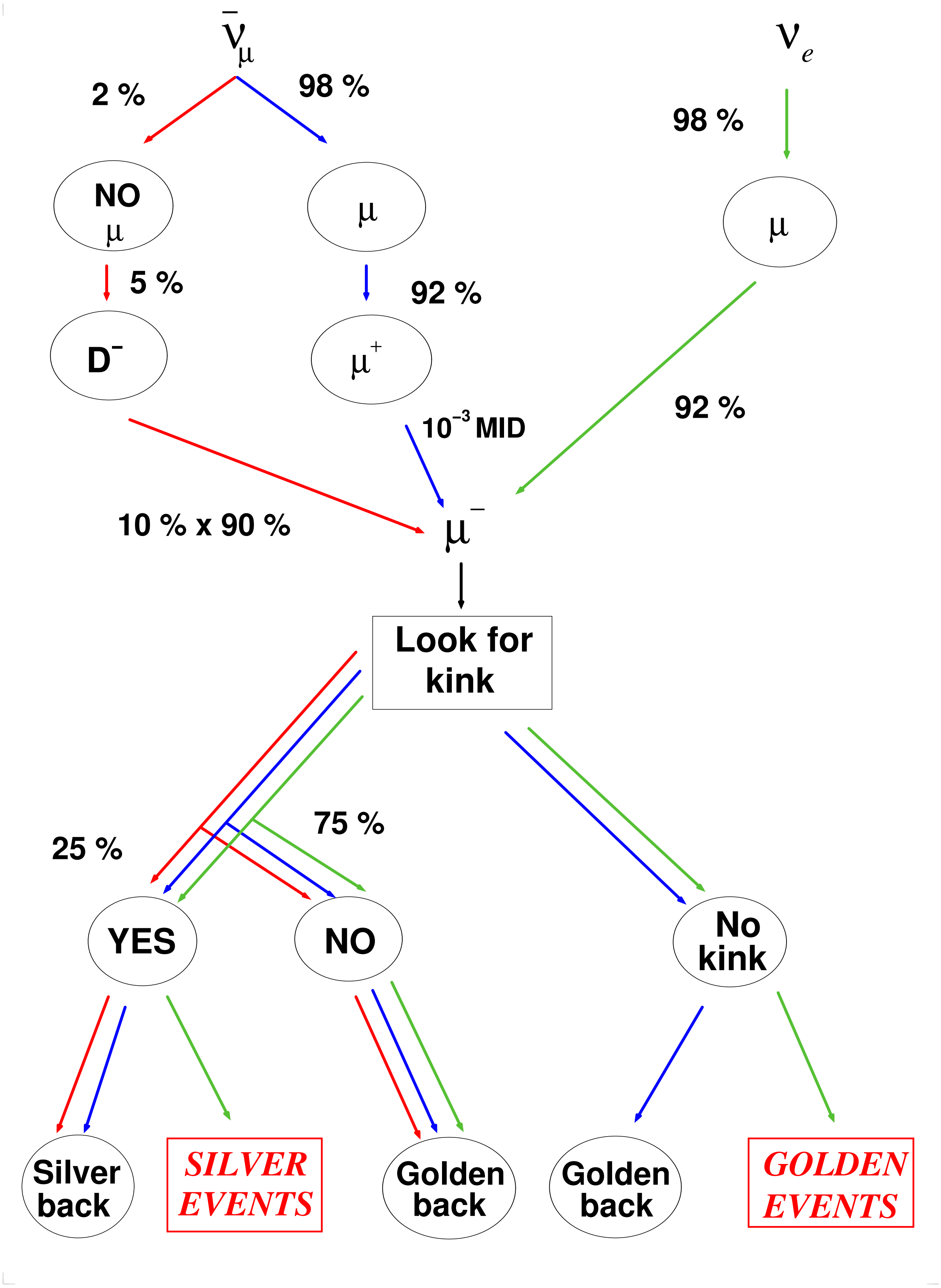
- ▷ GOLDEN muons backgrd (B_{golden}) from charge misidentification
- ▷ SILVER muons backgrd (B_{silver}) from D^- decays (see figure below)



$\Downarrow$

look at the SILVER MUONS energy distribution to increase the S/B ratio at low energy

Signal and background



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 combination:

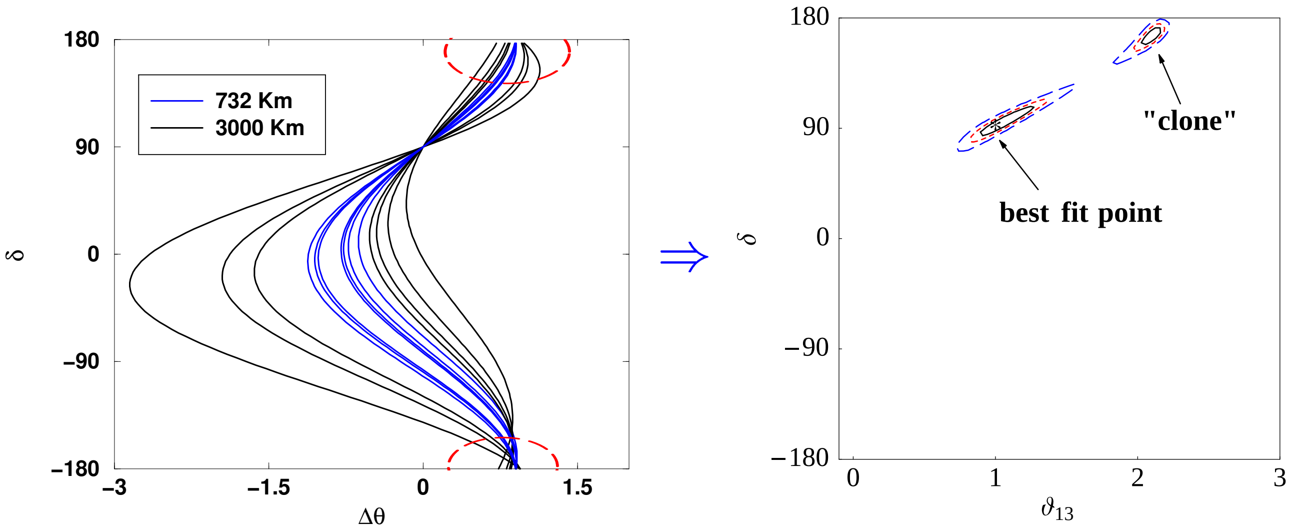
- (A) two 40 Kton iron detectors
  at $L = 732$ and $L = 3000$ Km
- (B) one 40 Kton iron detector at $L = 3000$ and
  one 2 Kton emulsion detector at $L = 732$ Km

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

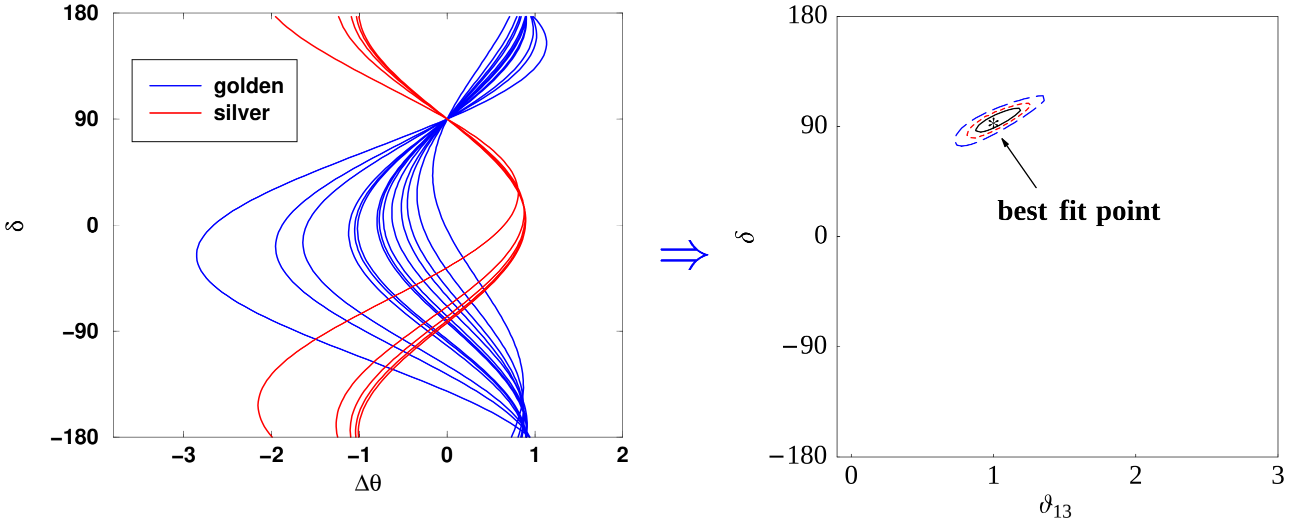
- iron detector: golden muons
- emulsion detector: golden and silver muons

Using golden and silver muons

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



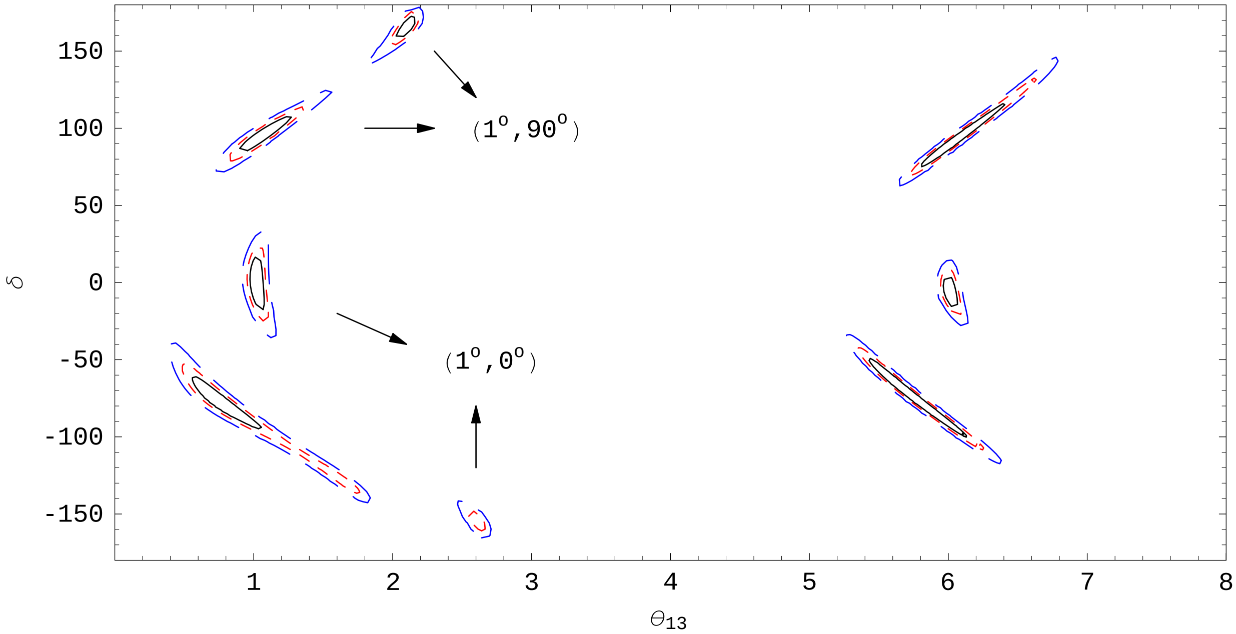
Setup B: one iron and one emulsion detectors
(golden and silver muons; IDEAL emulsion detector)



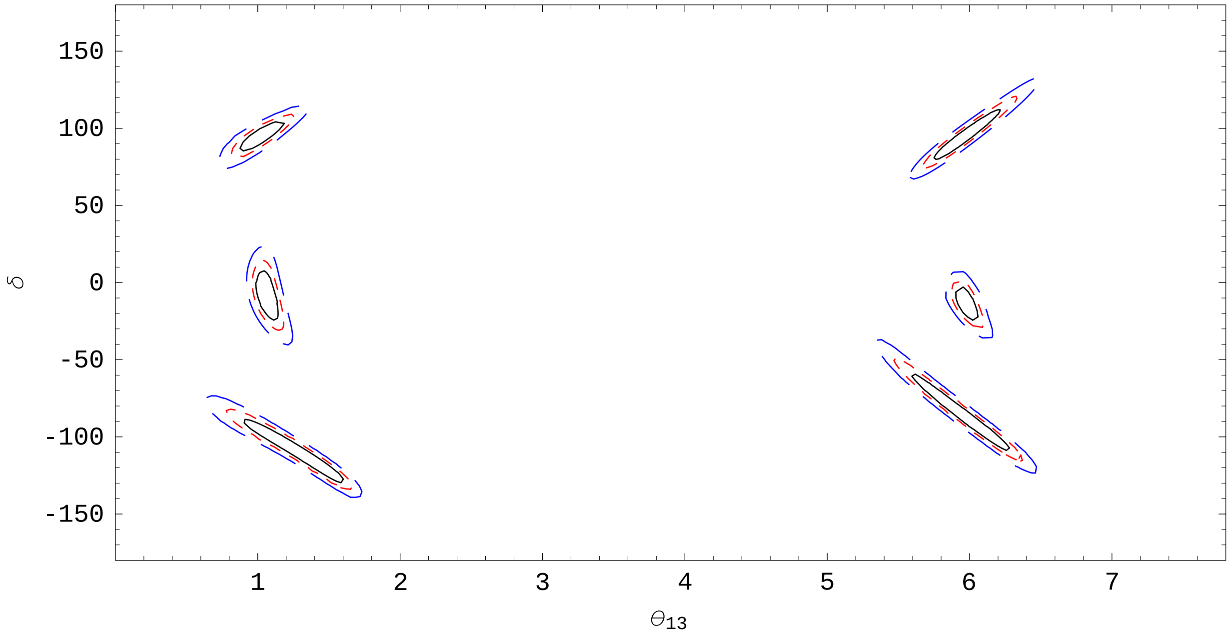
Input parameters: $\bar{\theta}_{13} = 1^\circ, \bar{\delta} = 90^\circ$

The ideal case

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

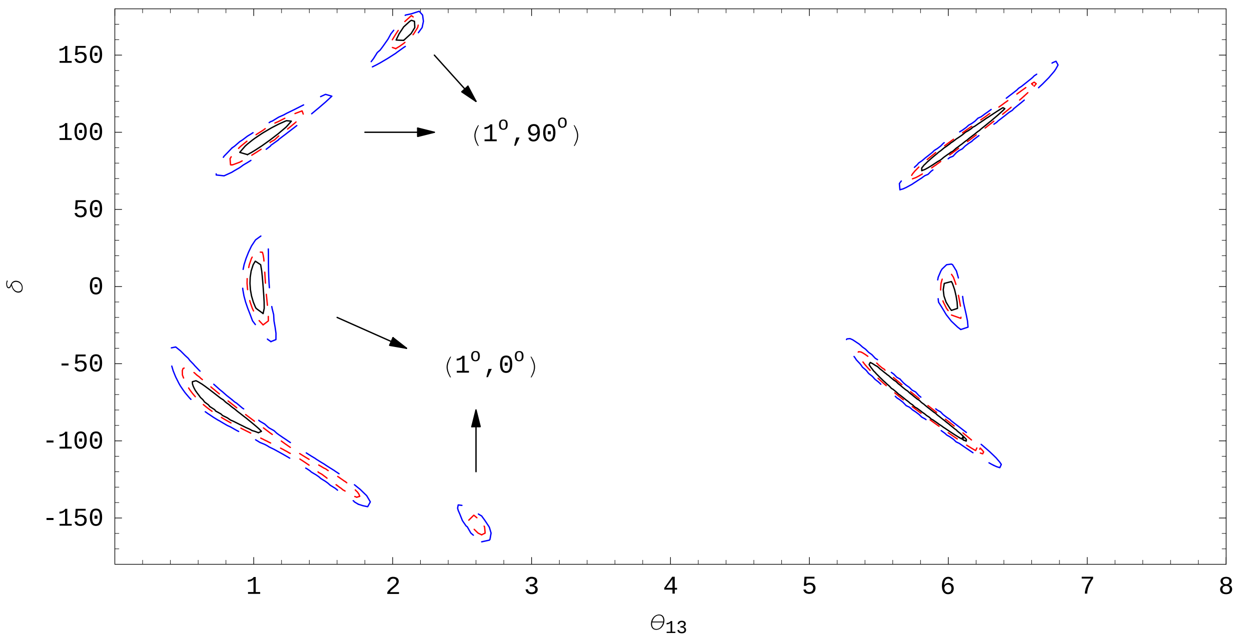


Setup B: one iron and one emulsion detectors (golden and silver muons; IDEAL emulsion detector)

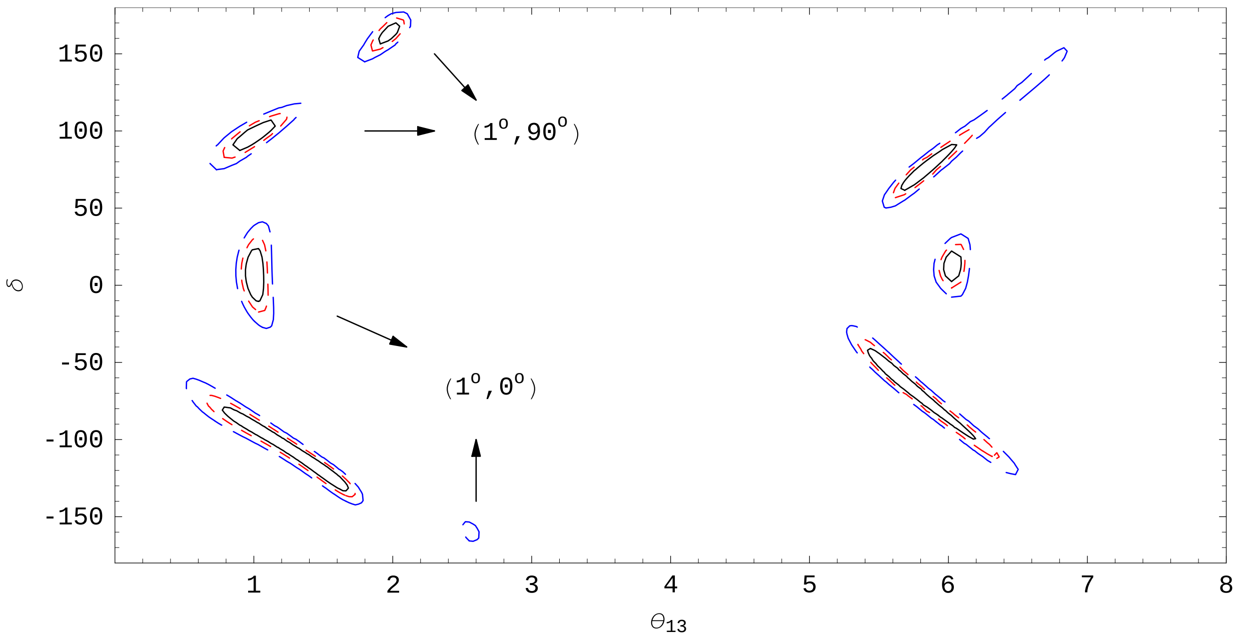


The real case

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	δ_{min},δ_{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 decreases the statistical significance of the "clone" zones

Conclusions

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

$\triangleright$ $\nu_e \to \nu_\tau$ 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 $\theta_{13} \geq 1^\circ$.