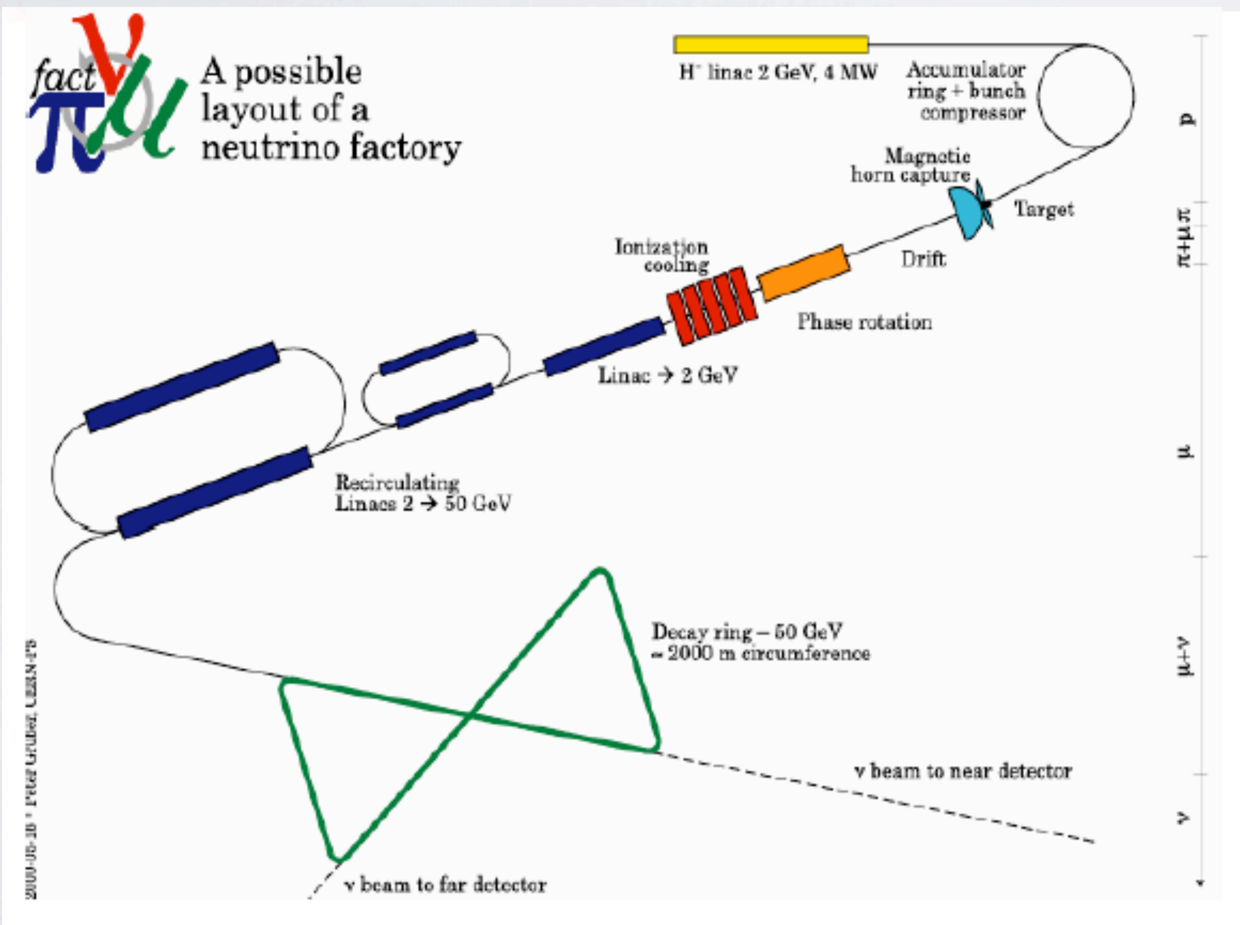
# PHYSICS OF THE NEUTRINO FACTORY (AND FRIENDS)




J.J. Gómez Cadenas
IFIC (CSIC-UV)

Lecture III

# DEGENERATE PHYSICS

$$P_{atm} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{1.267\Delta m^2_{atm}L}{E}\right) \rightarrow X\theta^2_{13}$$

$$P_{sun} = \cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\left(\frac{1.267\Delta m^2_{sol}L}{E}\right) \rightarrow Z$$

$$P_{\text{int}} = \cos\left(\pm\delta - \frac{1.267\Delta m^2_{atm}L}{E}\right)\left(\frac{1.267\Delta m^2_{sol}L}{E}\right)\sin\left(\frac{1.267\Delta m^2_{atm}L}{E}\right) \rightarrow$$

$$\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\left(\frac{\Delta_{12}L}{2}\right)\sin\left(\frac{\Delta_{23}L}{2}\right)\cos\left(\pm\delta - \frac{\Delta_{23}L}{2}\right) \rightarrow$$

$$\theta_{13}Y\cos\left(\pm\delta - \frac{\Delta_{23}L}{2}\right)$$

$$P_{\nu,\bar{\nu}} = X\theta^2_{13} + \theta_{13}Y\cos\left(\pm\delta - \frac{\Delta_{23}L}{2}\right) + Z$$

- Suppose you make an experiment with a fixed polarity (neutrinos) and fixed energy and baseline. The outcome of your experiment is a measurement of P(ν,E,L). Your goal is to find the true value (chosen by Nature) of δ and $\theta_{13}$.

# DEGENERATE PHYSICS

$$P_{\nu,\bar{\nu}} = X\theta_{13}^2 + \theta_{13} Y \cos\left(\pm\delta - \frac{\Delta_{23} L}{2}\right) + Z$$

$$\text{True Values} \rightarrow (\bar{\theta}_{13}, \bar{\delta})$$

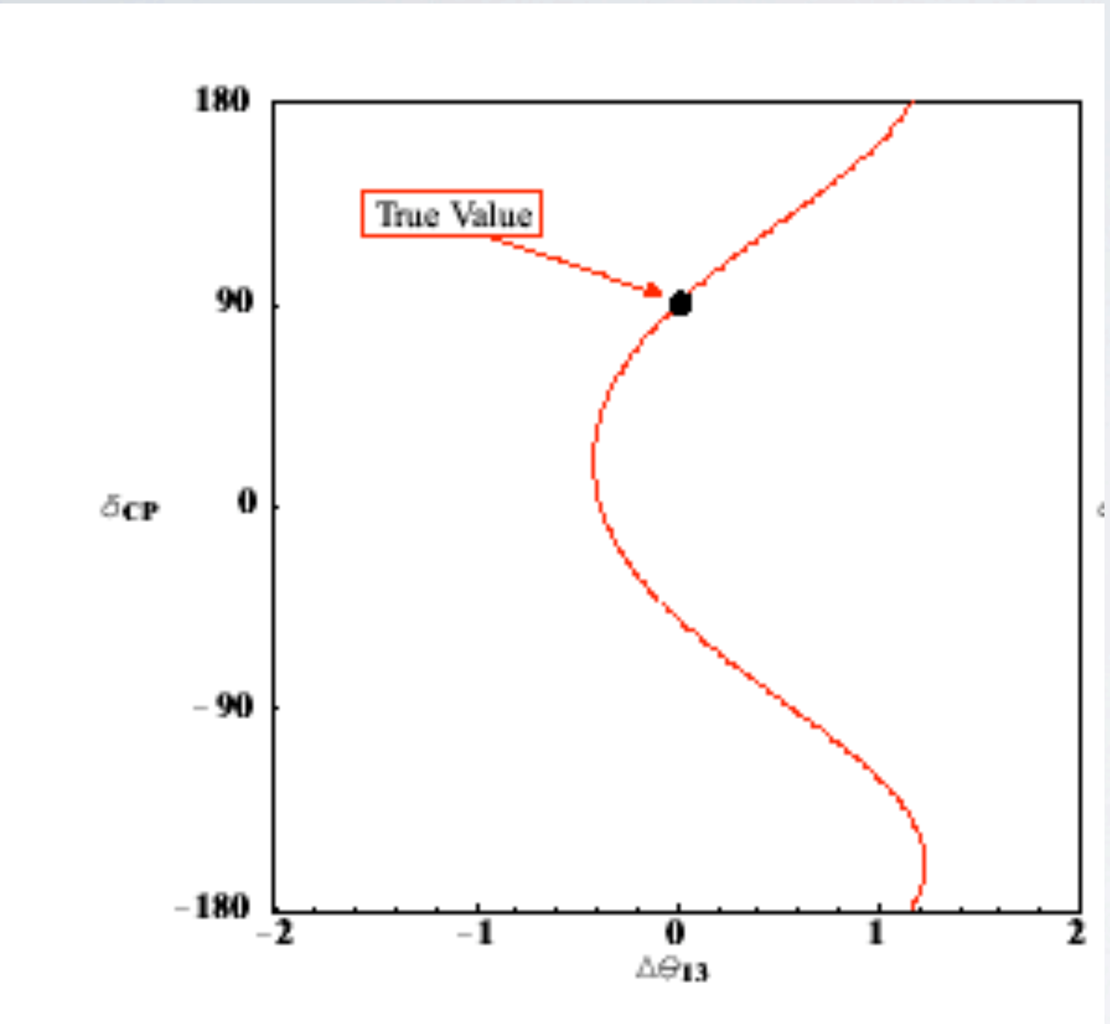
$$\text{True Result} \rightarrow P_{\nu,L,E}(\bar{\theta}_{13}, \bar{\delta}) = \alpha$$

$$\text{Ideal Measurement (no experimental error)} \rightarrow X\theta_{13}^2 + \theta_{13} Y \cos\left(\delta - \frac{\Delta_{23} L}{2}\right) + Z = \alpha$$

$$\text{Second order equation on } \theta_{13} \rightarrow \theta_{13} = -\frac{Y}{2X}\cos\left(\delta - \frac{\Delta_{23} L}{2}\right) \pm \left[\left(\frac{Y}{2X}\cos\left(\delta - \frac{\Delta_{23} L}{2}\right)\right)^2 + \frac{1}{X}(\alpha - Z)\right]$$

- θ13 and δ are related by a the solution of a second order equation. What is the result...?

# DEGENERATE PHYSICS



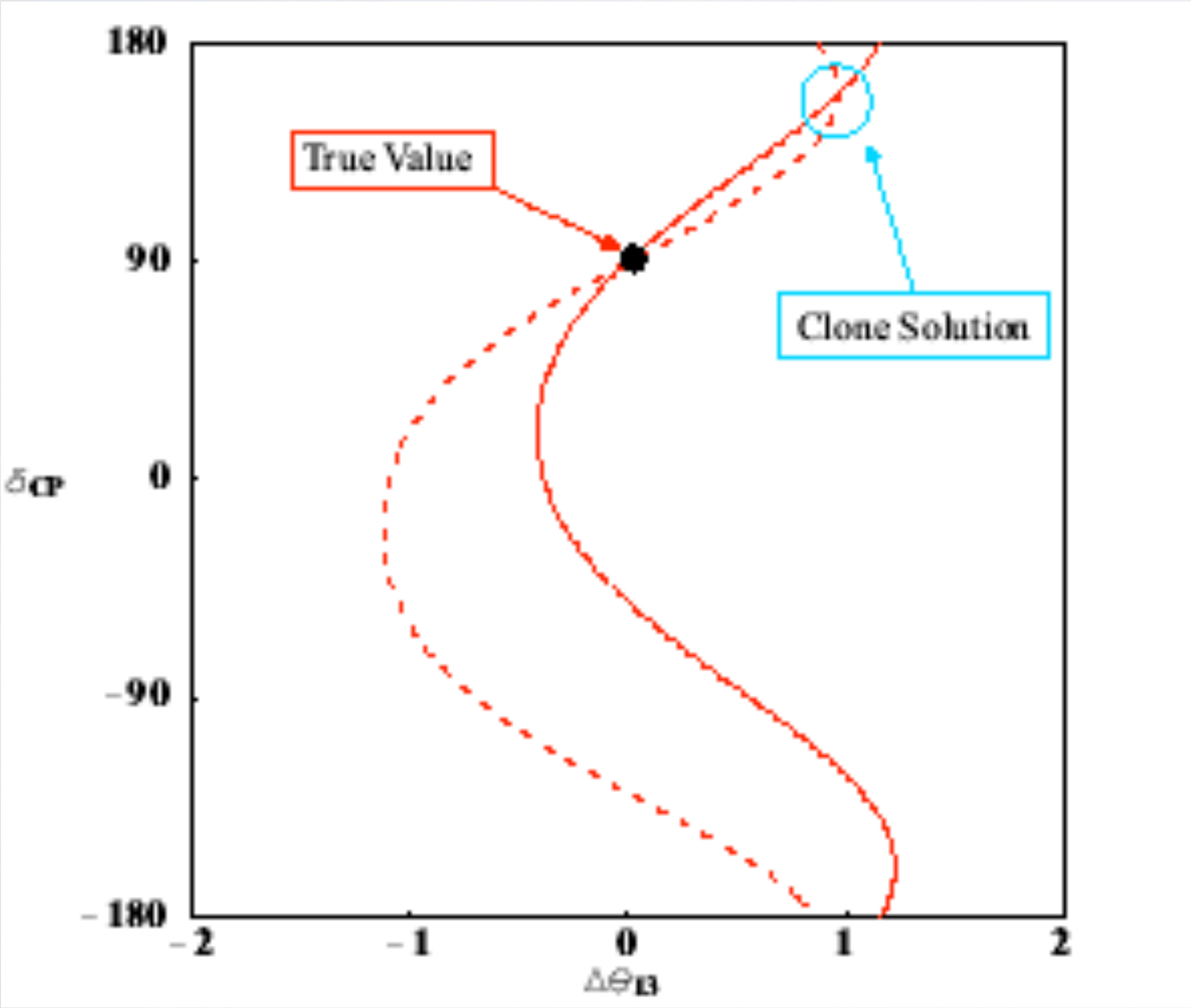

- We obtain a curve of equiprobability in the plane ($\theta_{13}$, $\delta$). The true solution is one of a continuous set and cannot be obtained if we fix polarity, baseline and energy.

- But one can now repeat the experiment using antineutrinos...

# DEGENERATE PHYSICS

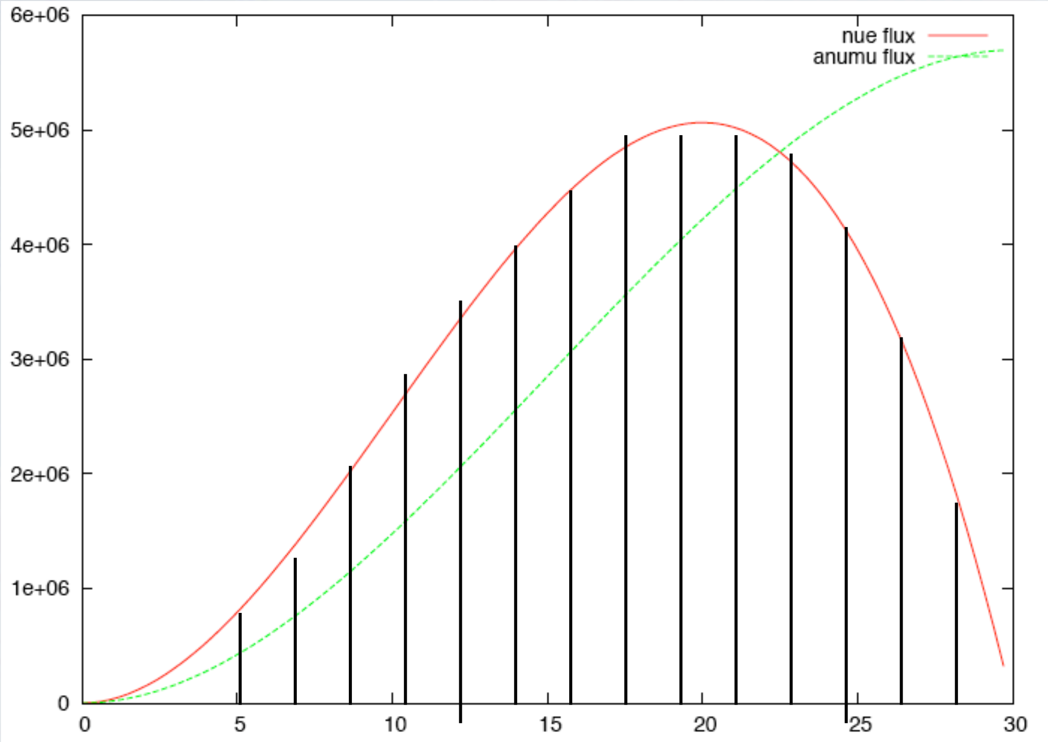
$$P_{\nu,L,E}(\bar{\theta}_{13},\bar{\delta})=\alpha_{\nu}\rightarrow\theta_{13}^{\nu}=-\frac{Y}{2X}\cos\left(\delta-\frac{\Delta_{23}L}{2}\right)\pm\left[\left(\frac{Y}{2X}\cos\left(\delta-\frac{\Delta_{23}L}{2}\right)\right)^{2}+\frac{1}{X}(\alpha_{\nu}-Z)\right]$$

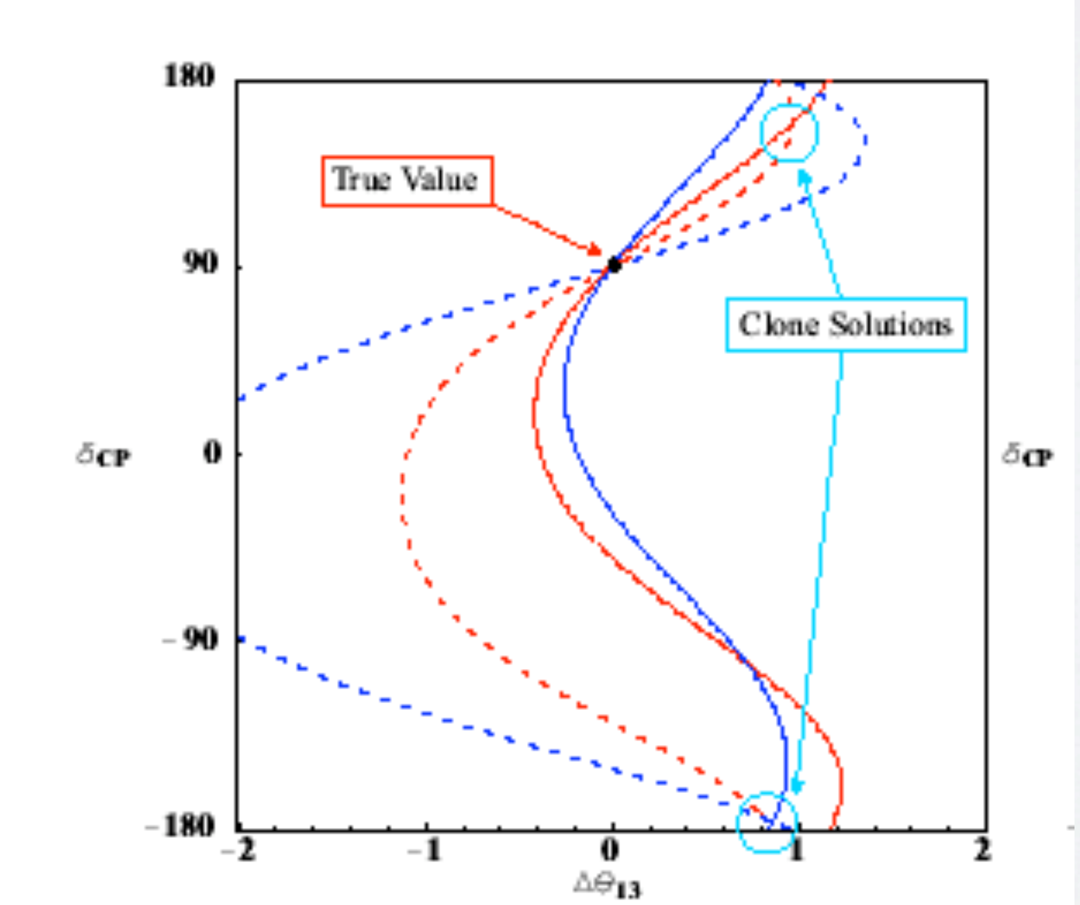
$$P_{\bar{\nu},L,E}(\bar{\theta}_{13},\bar{\delta})=\alpha_{\bar{\nu}}\rightarrow\theta_{13}^{\bar{\nu}}=-\frac{Y}{2X}\cos\left(-\delta-\frac{\Delta_{23}L}{2}\right)\pm\left[\left(\frac{Y}{2X}\cos\left(-\delta-\frac{\Delta_{23}L}{2}\right)\right)^{2}+\frac{1}{X}(\alpha_{\bar{\nu}}-Z)\right]$$




- In this case we obtain two curves which cross at the true point. But, alas, these are periodic equations. If they cross in one point, they must cross in a second point!
- Thus the outcome of the experiment is a true solution and a clone! That is we find a degeneration in the solution, which is called the intrinsic degeneracy.

# DEGENERATE PHYSICS



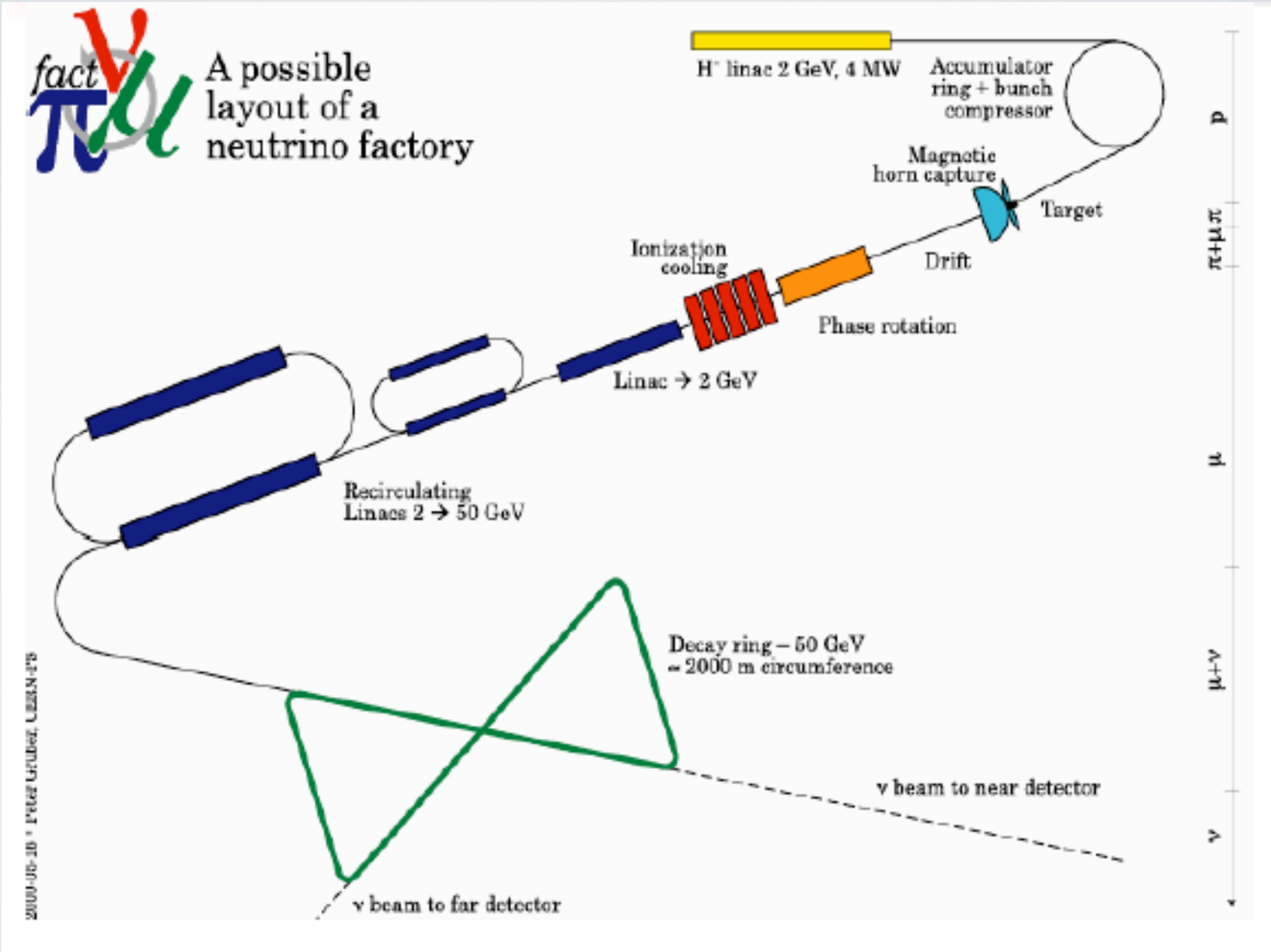




- Also (fortunately!) our beam is not monochromatic
- If we have good energy resolution, we can approximate our beam as a set of "monochromatic" beams.
- All monochromatic beam cross in the true point, but each one of them gives a different clone. Therefore, spectral analysis allows solving the degeneracy!

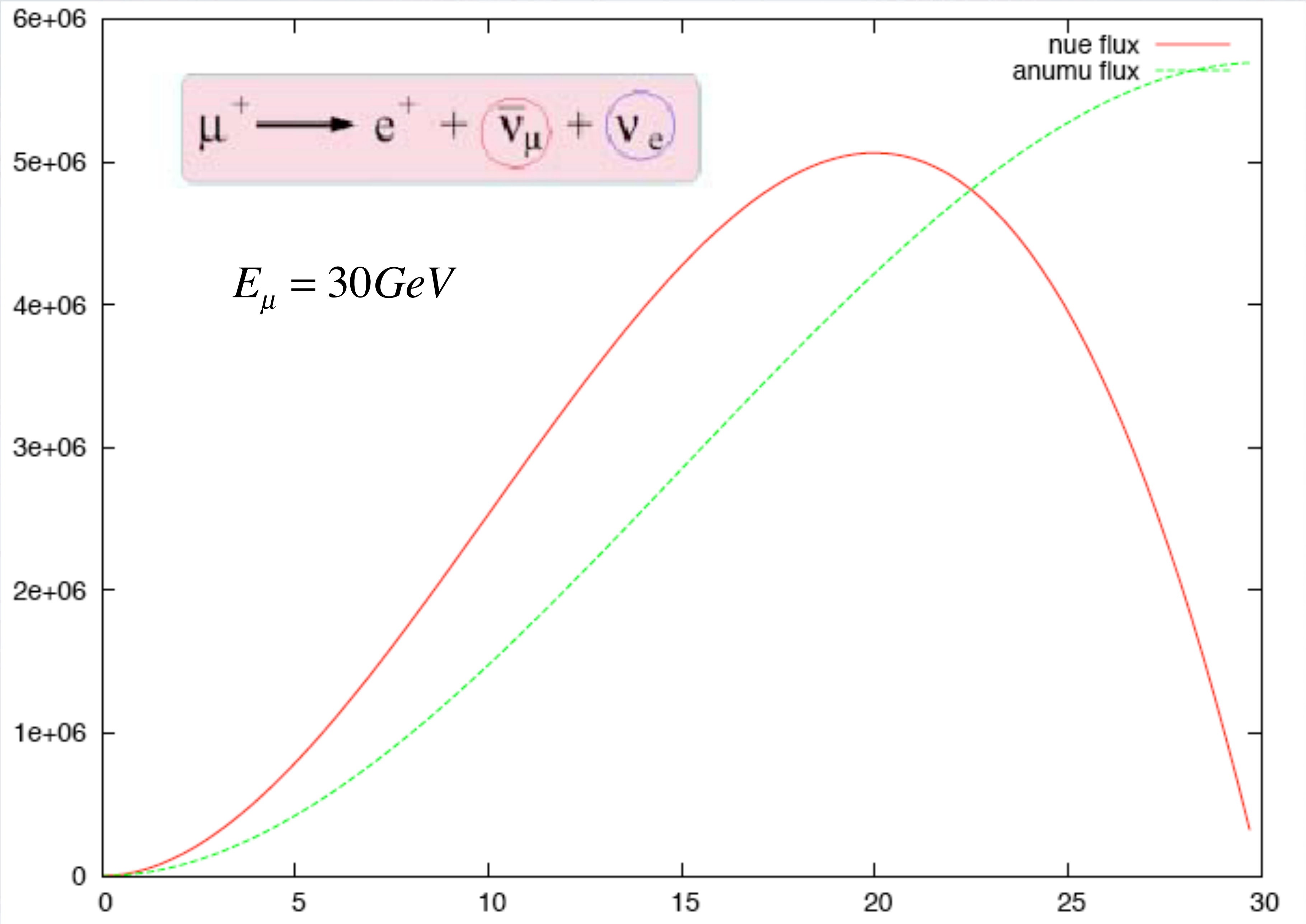
# HOMEWORK

- Consider three different experiments. One with a super-beam (conventional), another with a beta-beam and another with a neutrino-factory.
- Will degeneracies appear in all of them?
- Do you need to use always neutrinos and antineutrinos to solve the degeneracy? Why?
- Which machine gives you, a priory, the best chances to break the intrinsic degeneracy?
- Which neutrino energy would you settle for?

# THE NEUTRINO FACTORY



# BEAMS



$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$
$E_\mu = 30 GeV$
nue flux
anumu flux
6e+06
5e+06
4e+06
3e+06
2e+06
1e+06
0
0
5
10
15
20
25
30

# GOLDEN AND SILVER CHANNELS

**The Golden Channel at the Neutrino Factory**

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

The oscillation probability is

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

**The Silver Channel at the Neutrino Factory**

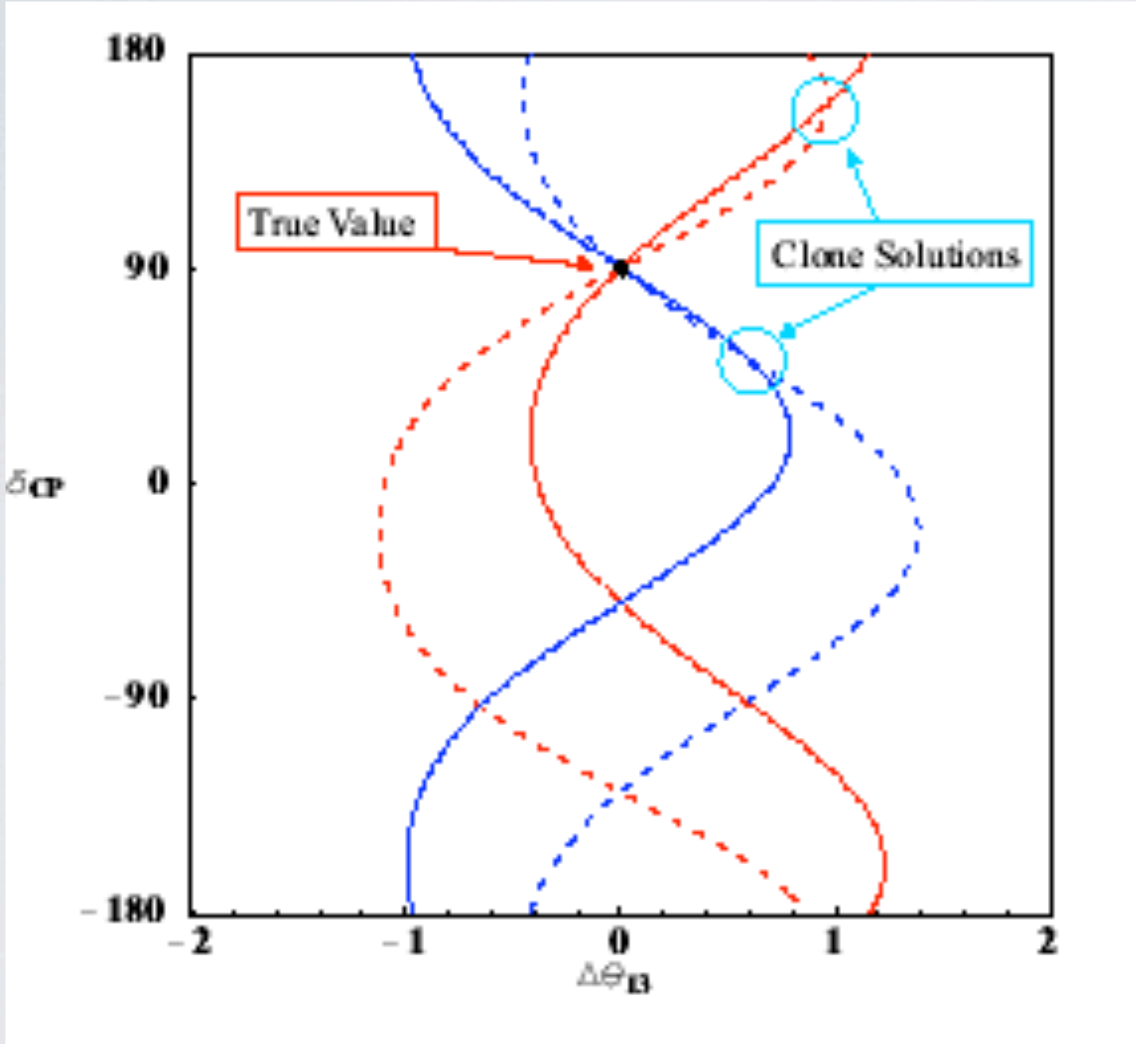
$$\mu^+ \to \begin{cases} e^+ \\ \bar{\nu}_\mu \\ \nu_e \to \nu_\tau \to \tau^- \to \mu^- \end{cases}$$

The oscillation probability is

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

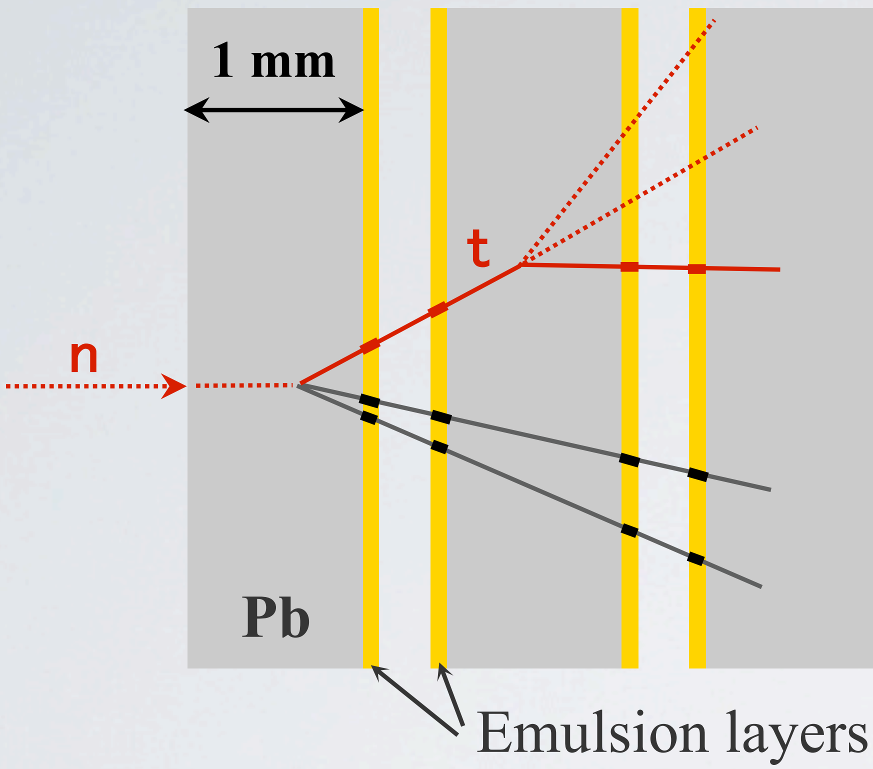
- The oscillation probability for the subleading oscillation eμ and eτ differ in a sign, thus...

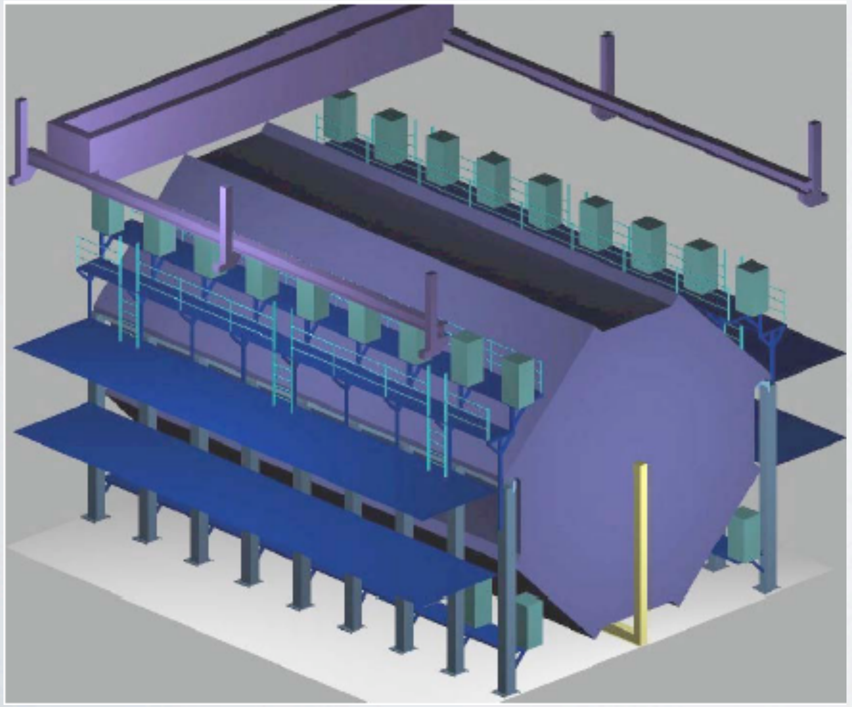
# GOLDEN AND SILVER CHANNELS




- If one has a tau-capable detector then the combination of golden and silver channels, helps further the spectral analysis.
- Golden and Silver solutions cross in the true value and each one has a clone, but these are different clones! Thus one can solve the system and eliminate degeneracy.

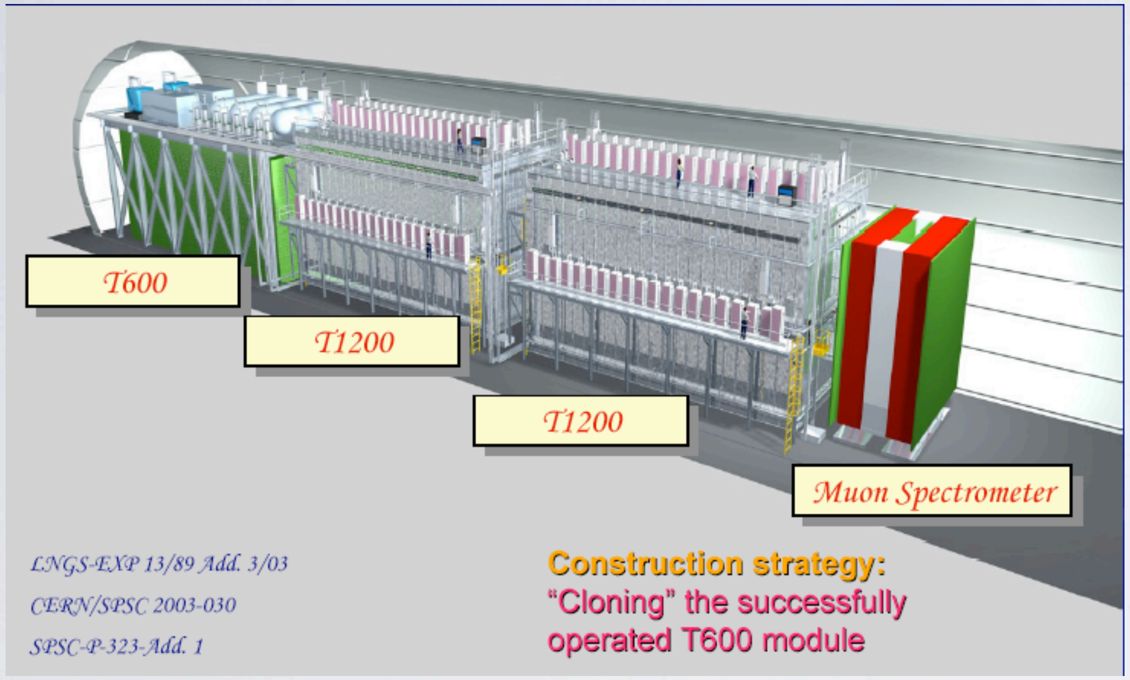
# OPERA-LIKE TAU DETECTORS

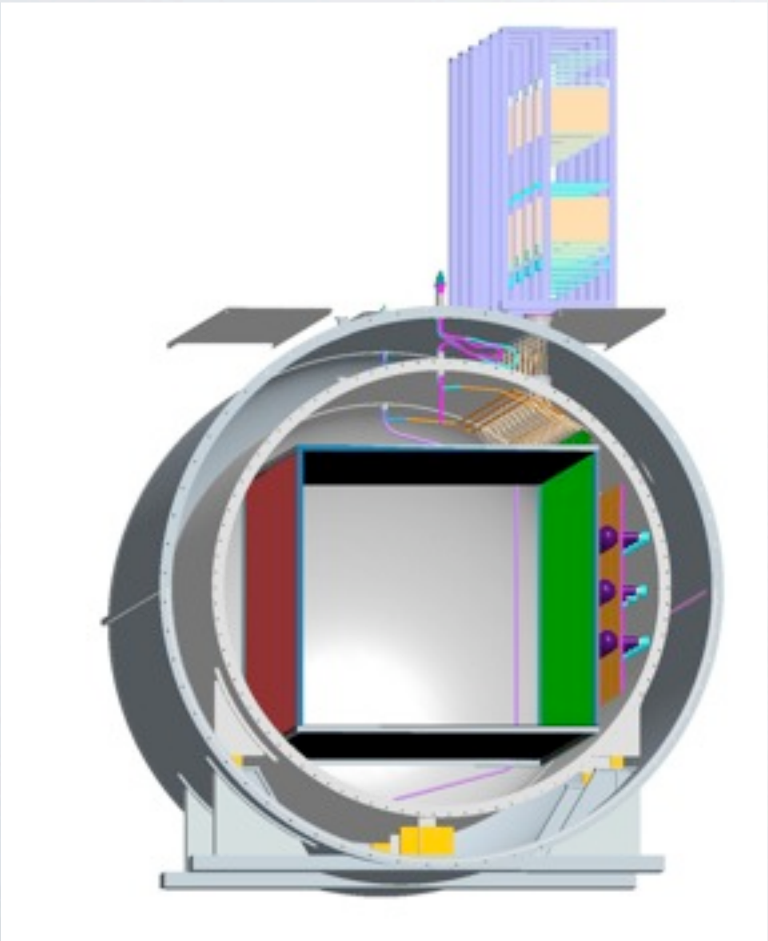


- hybrid detectors that use emulsion targets to identify tau vertex
- Based on "topological" signature, a la CHORUS and NOMAD

# NOMAD-LIKE (ICARUS TYPE) DETECTORS



- Large liquid argon chambers
- Capable of providing a tau "kinematical" signature, "a la NOMAD"
- ICARUS was like fusion. Always in the promising future...
- But Micro-boone is here!

# HOMEWORK

- Consider a OPERA-Like and a ICARUS-like detector to study the tau-channel at a neutrino factory
- Which mass do you think the OPERA-like detector can afford? And the ICARUS-like? Why?
- Which one is more scalable?
- Who will have better background control?
- You are the new Fermilab director in charge of choosing a detector for the tau channel. Go ahead, and give me mass scale, construction time and budget!
- (worried about blundering? Think about CERN D.G....)

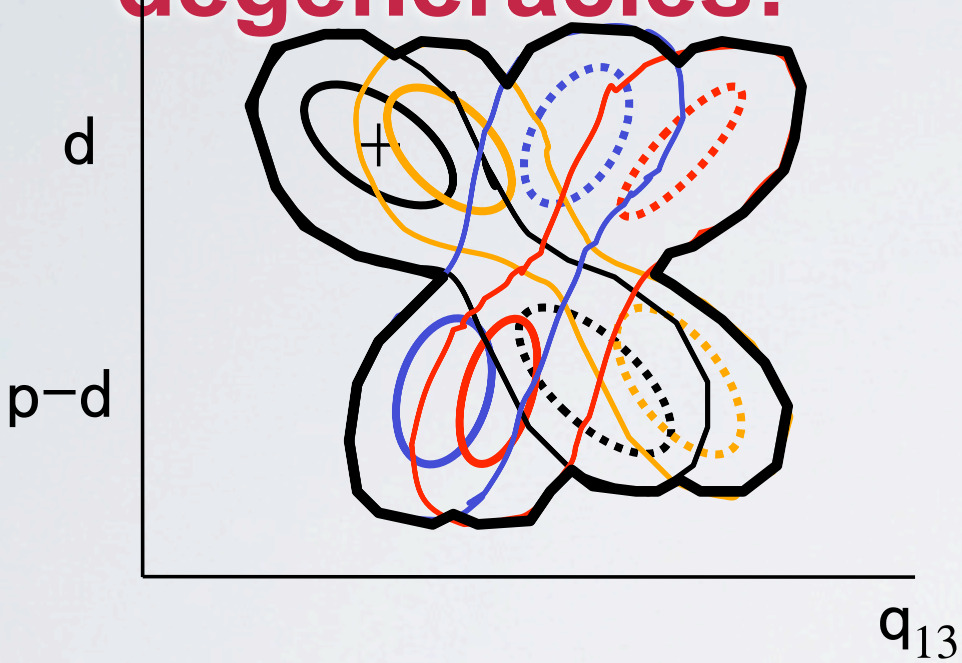
# DISCRETE DEGENERACIES

$$s_{atm} = \mathrm{sgn}(\Delta m_{23}^2) \qquad s_{oct} = \mathrm{sgn}(\tan(2\theta_{23}))$$

- When you are doing your fit... ¿do you know a priory the sign of $\Delta m_{23}$? You don't and this is introducing you a discreet degeneracy (two possible values +1 and -1) which becomes more relevant for experiments which have to deal with serious matter effects (e.g, NUFACT)
- The same thing happens if $\theta_{23}$ is not exactly maximal. Then you don't know exactly in which quadrant the angle is. This introduces a second discreet degeneracy.

# CORRELATIONS AND DEGENERACIES

- **Discrete degeneracies:**




**2 intrinsic degeneracies**

**x 2 possible hierarchies**

**x 2 possible $q_{23}$ octants**

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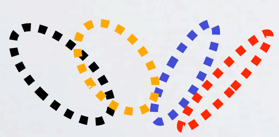
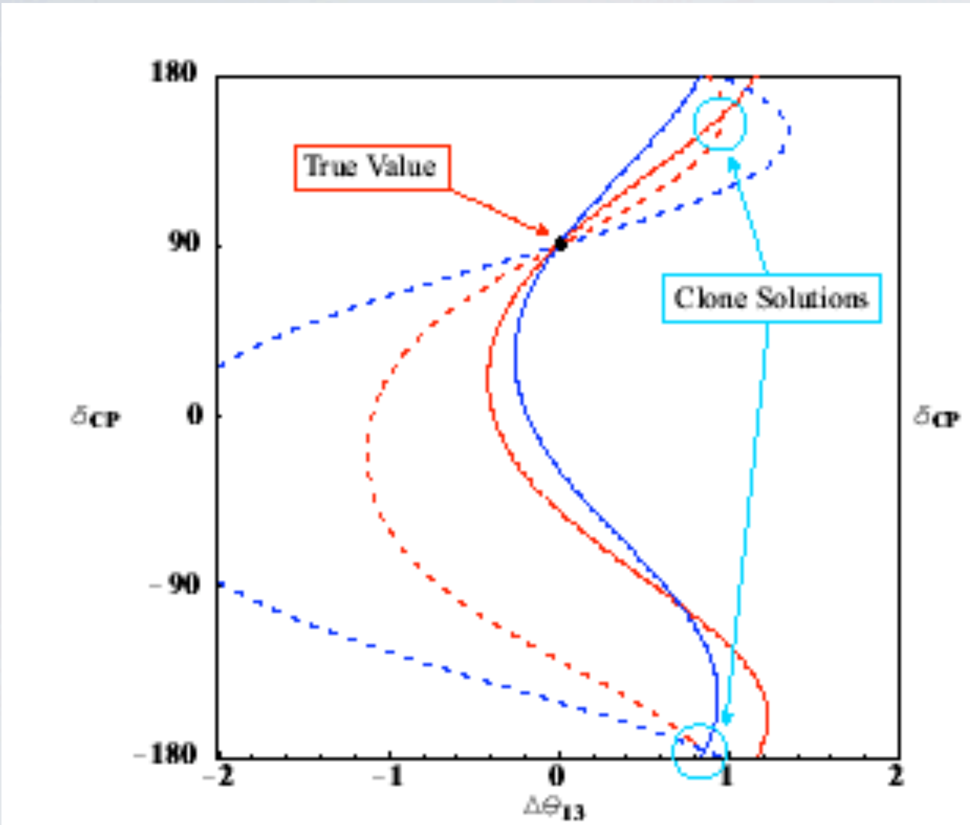
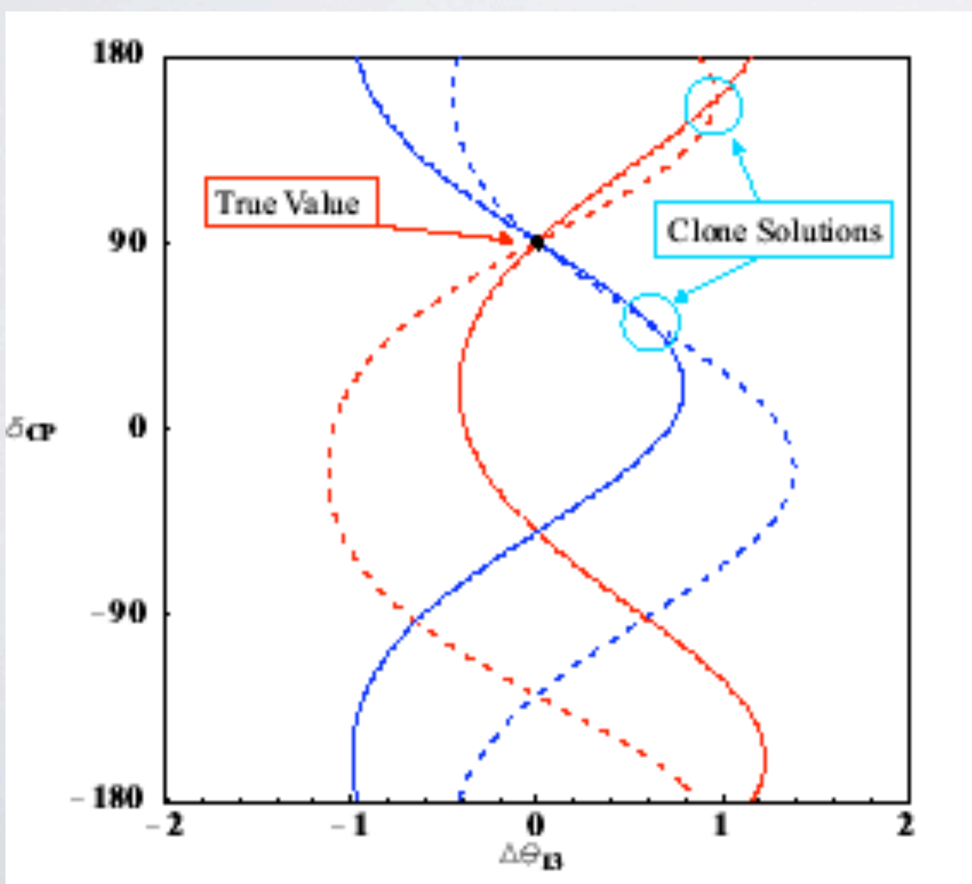
**= 1 true solution + 7 clones!!**

- Each color belongs to a different parameter space.
- Intrinsic fake solution and its clones  depend strongly on E/L ratio (unlike the clones of the true solution ).
-  greatly increase the errors, particularly for d.

# RECIPES TO SOLVE DEGENERACIES




- Use spectral information on oscillation signals: experiment with energy resolution
- Combine experiments differing in E/L (and/ or matter effects): need two experiments
- Include other flavor channels: silver channel: Need a tau-capable detector