Monochromatic Neutrino Beams and CP Violation in Neutrino Oscillations

Peter Fest
5 May 2006

J. Bernabeu
U. de Valencia and IFIC

JHEP 0512:014, 2005
hep-ph/0505054

Monochromatic Neutrino Beams and CP Violation in Neutrino Oscillations

- What is known, what is unknown
- Interest of energy dependence in neutrino oscillations
- Gamow-Teller resonance in electron capture
  → Definite neutrino energy
- Neutrino flux in LAB frame
- Physics reach
- Feasibility and prospects

What is known, what is unknown

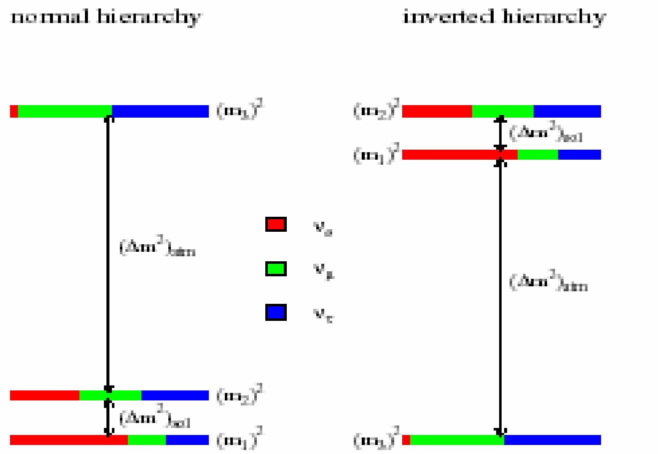
- **Neutrino flavour oscillations**

$$\begin{cases} \Delta m^2{}_{23} = 2.4 \times 10^{-3} eV^2 & \sin^2 2\theta_{23} = 1.00 \\ \Delta m^2{}_{12} = 8 \times 10^{-5} eV^2 & \sin^2 2\theta_{12} = 0.81 \\ \theta_{13} < 10^o & \delta \quad ? \end{cases}$$

- **Absolute neutrino masses ?** → ^3H beta decay

- **Form of the mass spectrum**

  →Matter effect in neutrino propagation



- **Majorana neutrinos** ? → 0νββ: masses and phases

Interest of energy dependence in neutrino oscillations

- After atmospheric and solar discoveries and accelerator and reactor measurements → θ□□ , δ
- □□ □□□□□□□□□□ □□□□□□□□□□□ □□ □□□□□□□□□□□ □□□□□□□□□□□□

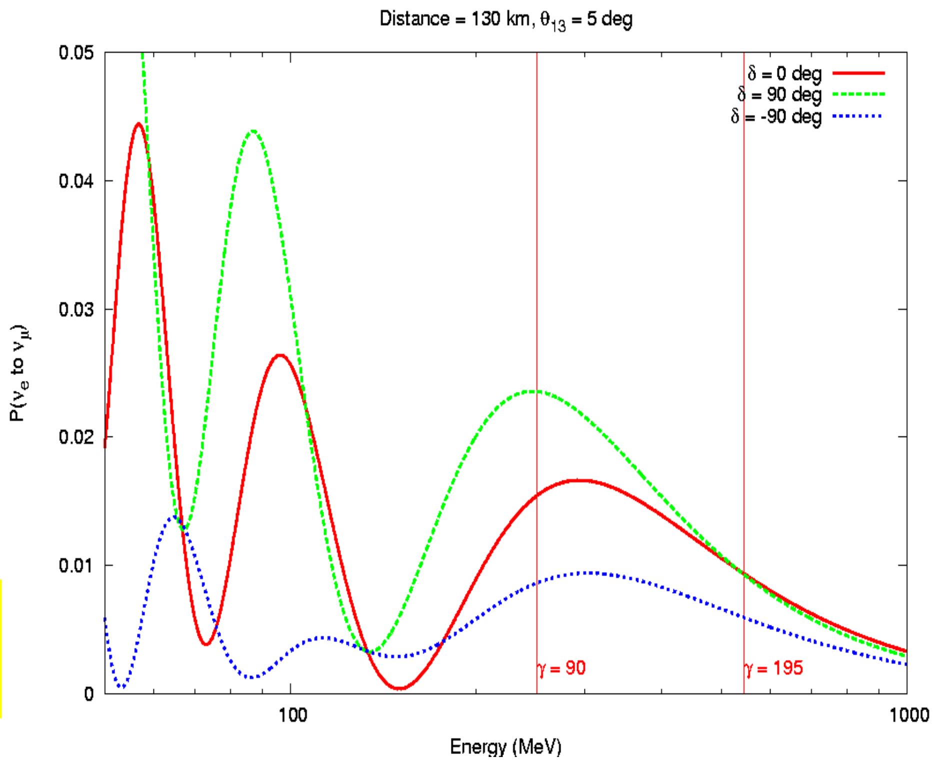
Appearance probability:

$$P(\nu_e \to \nu_\mu) \approx \underbrace{s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{13}^2 L}{4E}\right)}_{\text{Atmospheric}} +$$

$$\underbrace{c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{12}^2 L}{4E}\right)}_{\text{Solar}} +$$

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

|Ue3| gives the strength of $P(\nu_e \to \nu_\mu)$



δ acts as a phase shift

Interest of energy dependence in neutrino oscillations

- CP violation: $P(\nu_e \rightarrow \nu_\mu) \neq P(\overline{\nu}_e \rightarrow \overline{\nu}_\mu)$
- CPT invariance + CP violation = T non-invariance

$$P(\nu_e \rightarrow \nu_\mu) \neq P(\nu_\mu \rightarrow \nu_e)$$

- No Absorptive part → Hermitian Hamiltonian →

  CP odd = T odd = $P(\nu_e \rightarrow \nu_\mu) - P(\overline{\nu}_e \rightarrow \overline{\nu}_\mu)$
  is an odd function of time = L !

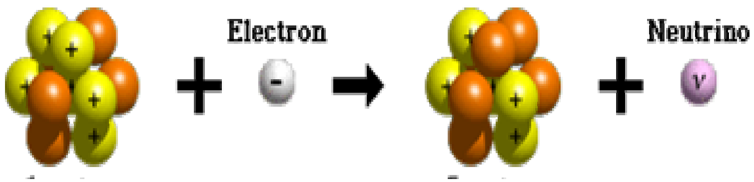
In vacuum neutrino oscillations → L/E dependence**, so**

This suggest the idea of a monochromatic neutrino beam to separate δ and |Ue3| by energy dependence!

Neutrinos from electron capture

How can we obtain a monochromatic neutrino beam?

Electron capture:

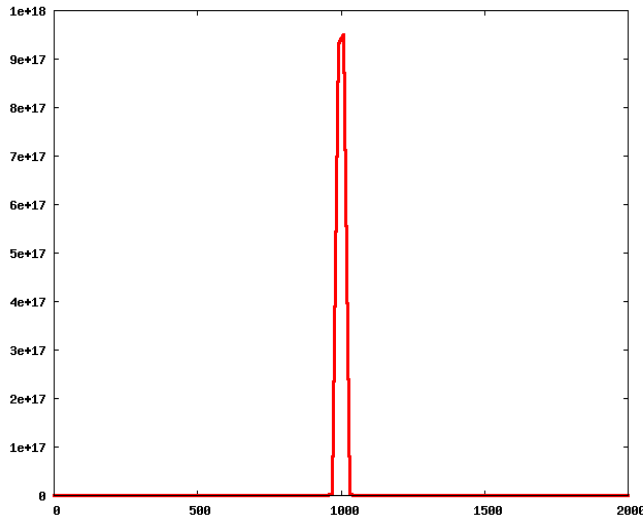


Z protons
N neutrons

Z-1 protons
N+1 neutrons

boost

Forward direction



2 body decay! → a single discrete energy if a single final nuclear level is populated

Flux:

Branching ratio

$$\frac{d^2N_\nu}{dSdE} = \frac{\Gamma_{ec}}{\Gamma}\frac{N_{ions}}{\pi L^2}\gamma^2\delta(E-2\gamma E_0)$$

From the single energy e^--capture neutrino spectrum, we can get a pure and monochromatic beam by accelerating ec-unstable ions

Implementation

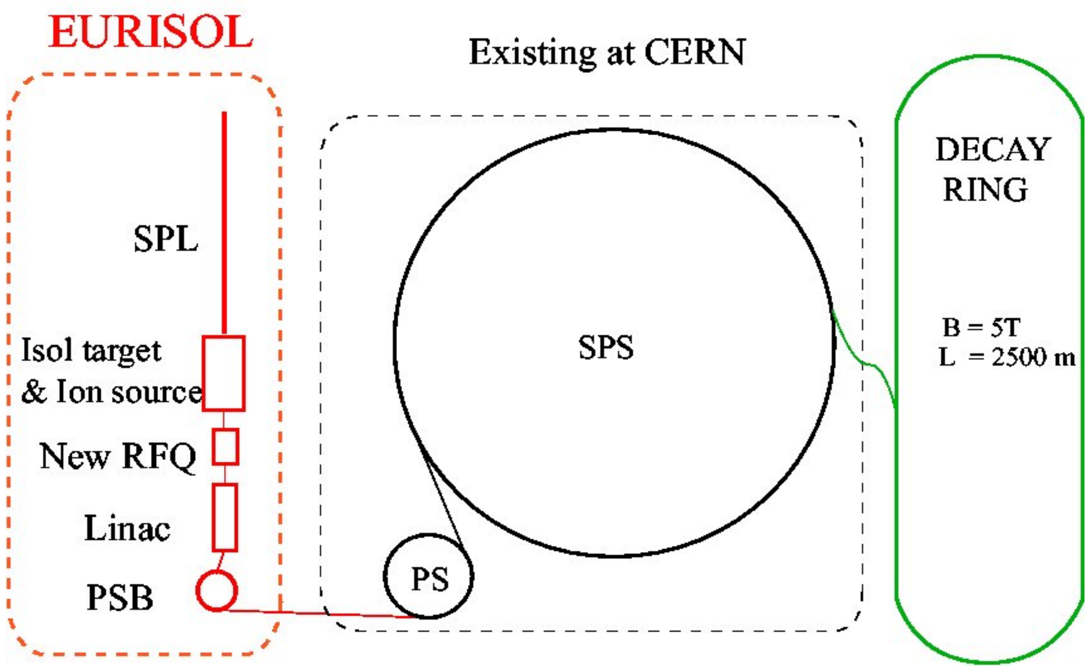
The facility would require a different approach to acceleration and storage of the ion beam compared to the standard beta-beam, as the atomic electrons of the ions cannot be fully stripped.

Partly charged ions have a short vacuum life-time. The isotopes we will discuss have to have a **half-life ≤ vacuum half-life ~ few minutes**.

For the rest, setup similar to that of a beta-beam.

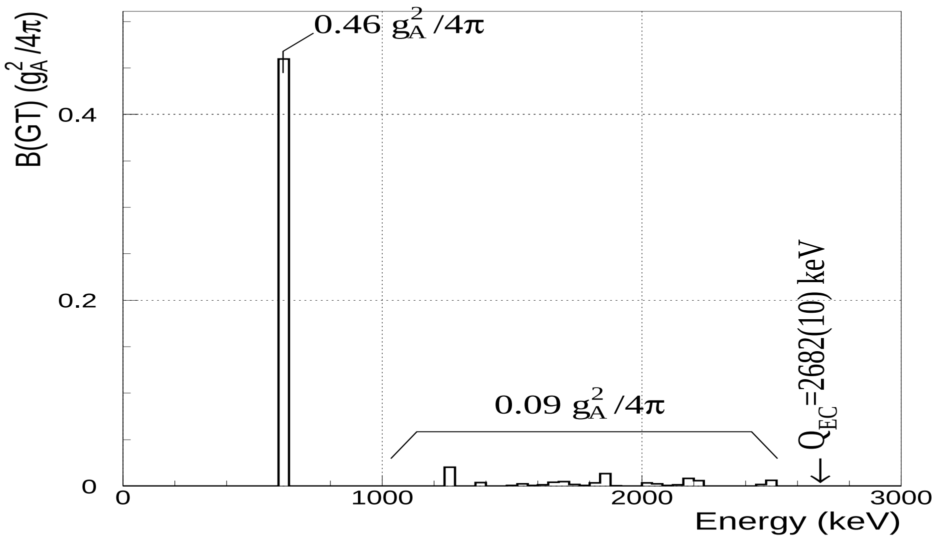
Brief recall :

- Ions produced at EURISOL
- Accelerated by the SPS
- Stored in a storage ring, straight sections point to detector

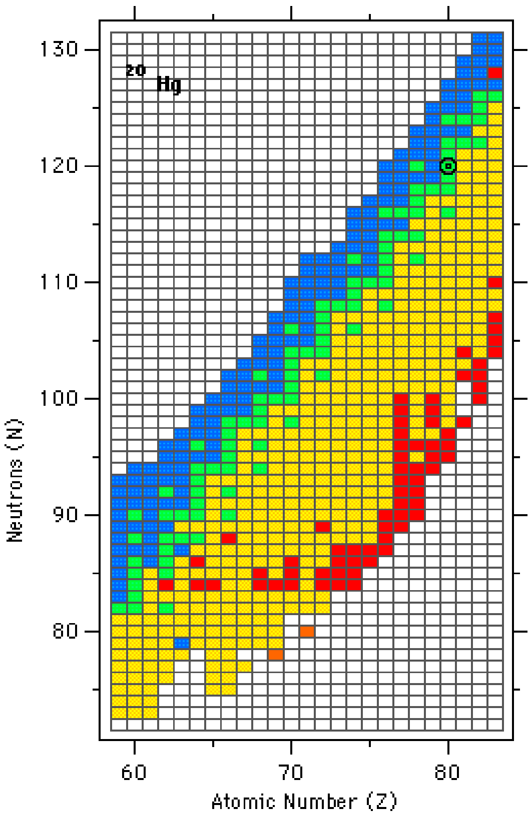


An idea whose time has arrived !

The “breakthrough” came thanks to the recent discovery of isotopes with half-lives of a few minutes or less, which decay mainly through electron capture to a single Gamow-Teller resonance in a super allowed transition.



Ion Candidates



Ions must have a mean life short enough to allow them to decay in the storage ring before they lose its electron.

The recent discovery of nuclei that decay fast enough through electron capture opens a window for real experiments.

We want to have an initial neutrino energy E_0 low so that a given $E=2\gamma E_0$ implies a high γ and then, for a high γ, higher neutrino flux.

Table 1: Beta decay properties of some rare-earth nuclei around ^{146}Gd

Decay	$T_{1/2}$	$I_{\beta GR}(\%)$	$B(GT)(g_A^2/4\pi)$	E_{GR}(keV)	Γ_{GR}(keV)	$E_\nu=Q_{EC}-E_{GR}$(keV)	ΔE_ν(keV)	EC/β^+(%)	Comments
^{148}Dy→^{148}Tb	3.1 m	96.2	0.46	620.2	—	2061.8	—	96/4	excellent!
^{150}Dy→^{150}Tb	7.17 m	100	0.32	397.2	—	1396.8	—	99.9/0.1	36% goes α
^{152}Tm 2^- → ^{152}Er	8.0 s	≈50	0.48	≈4300	≈520	≈4400	≈520	45/55	
^{150}Ho 2^- → ^{150}Dy	72.0 s	≈56	0.25	≈4400	≈400	≈3000	≈400	77/33	

Physics reach

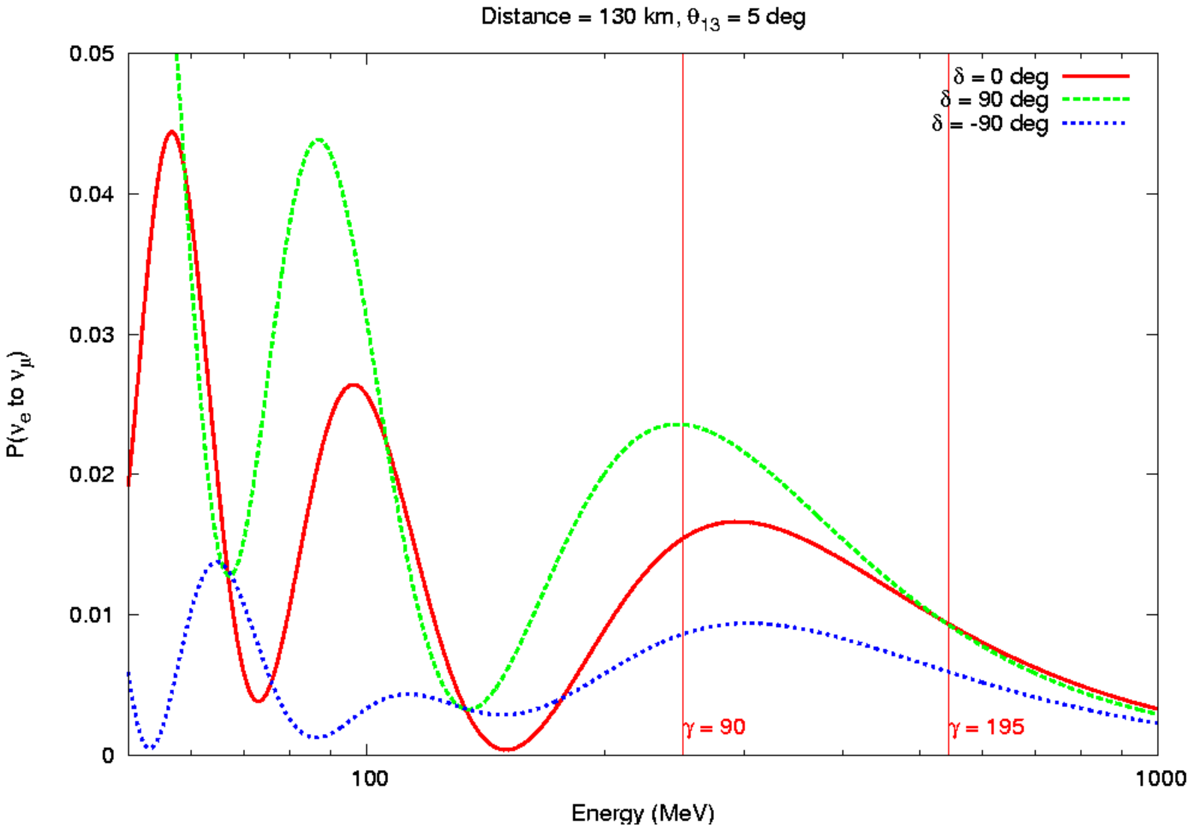
Setup

- { 5 years $\gamma =$ 90 (close to minimum energy above threshold)
  5 years $\gamma =$ 195 (maximum achievable at SPS)
- 10^{18} ions/year
- 440 kton water ckov detector

OR … appropriate changes
If higher production rates

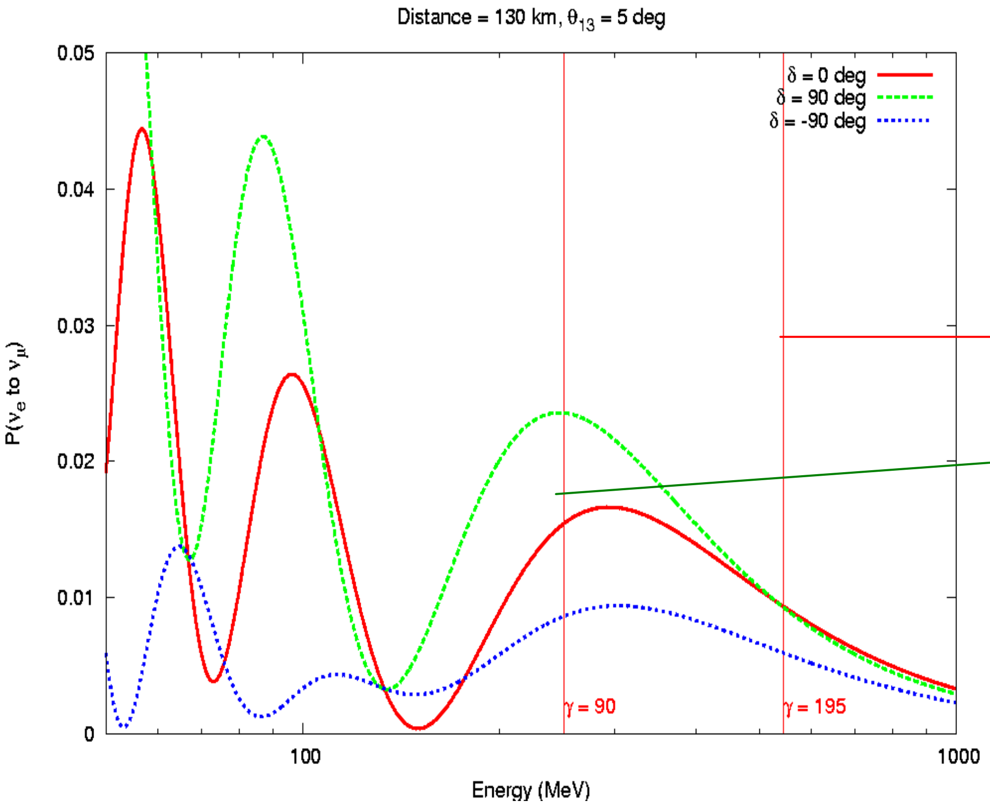
- Distance: 130 km (CERN-Frejus)

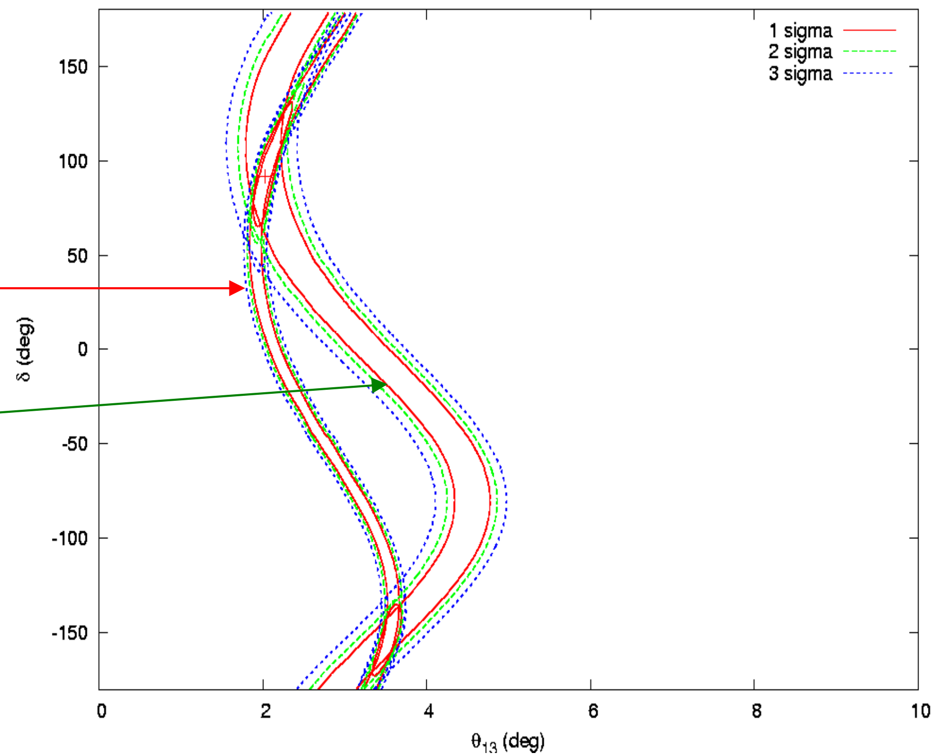
Appearance & Disappearance



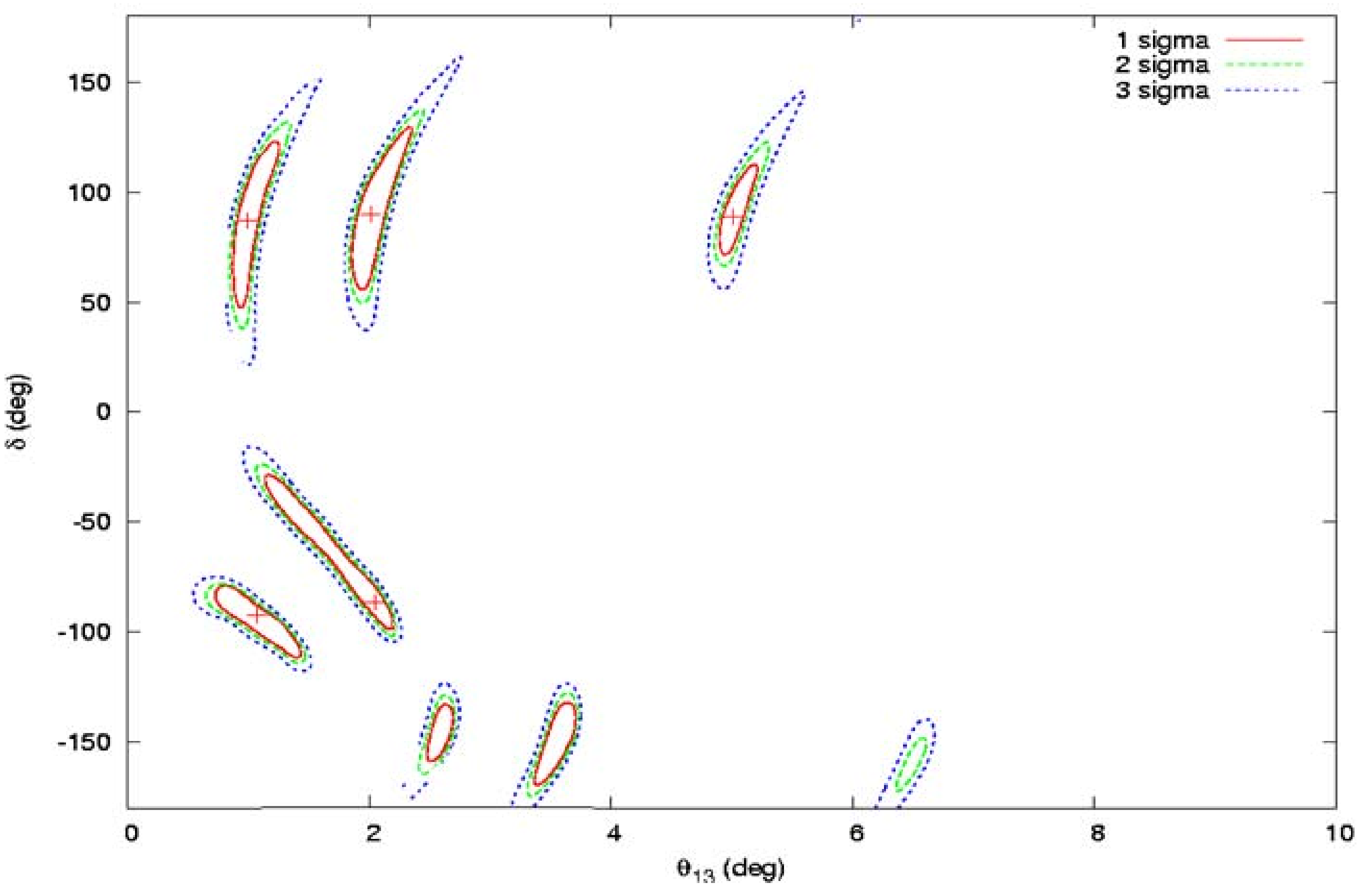
Preliminary results for two energies

130 km



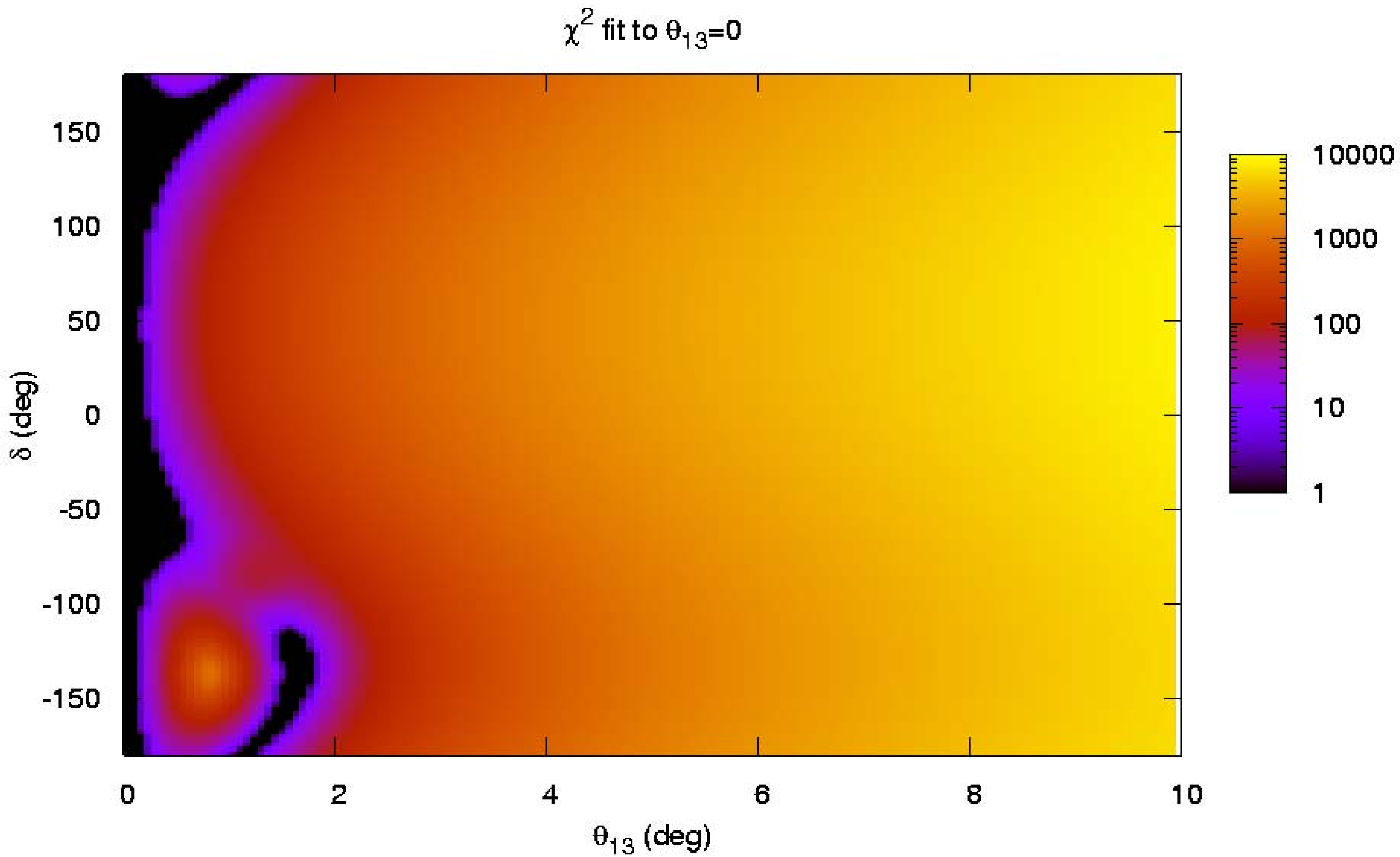


Fit of θ_{13} , δ from statistical distribution



The principle of an energy dependent measurements is working and a window is open to the discovery of CP violation

Exclusion plot: $\theta_{13} \neq 0$ sensitivity

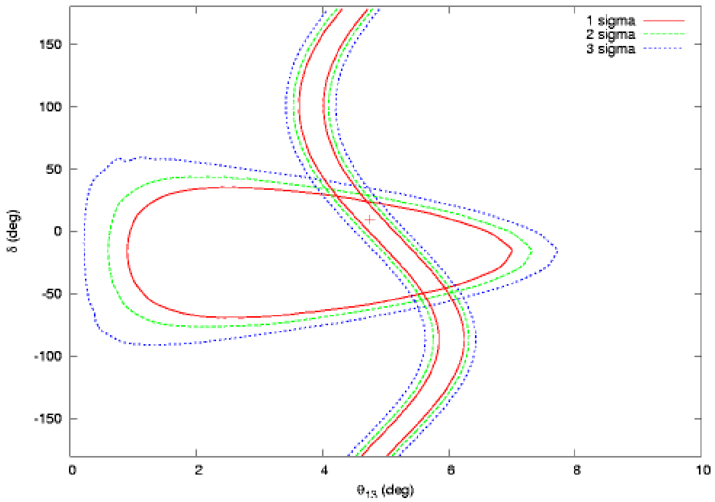


Total running time: **10 years**... Impressive!! Significant even at 1°

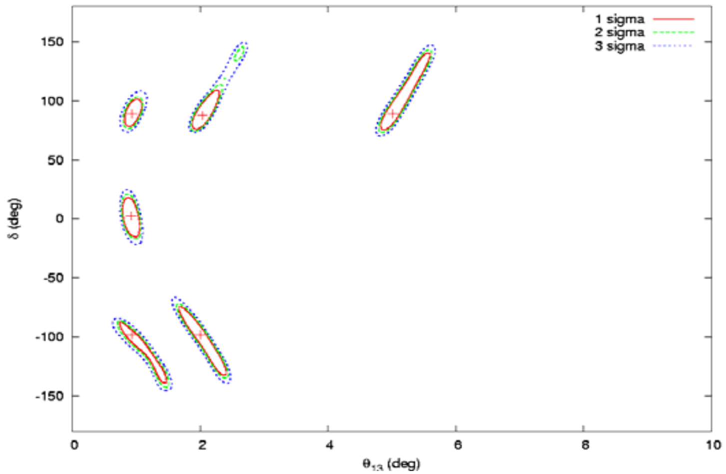
Access to a precise value of δ

1. Enter into the second oscillation in E/L, where the sensitivity to δ is higher → At fixed E, move to Canfranc: L=650 Km
   ... in study at present

650 Km



2. Check that the phase shift measured is the CP phase → combine EC ν with β^- (^{6}He) $\overline{\nu}$
   ... preliminary



Feasibility

- Acceleration and storage of partly charged ions

  - Experience at GSI and the calculations for the decay ring yield less than 5% of stripping losses per minute

  - A Dy atom with only one 1s electron left would still yield more than 40% of the yield of the neutral Dy atom

→ **with an isotope having an EC half-life of 1 minute, a source rate of 10^{13} ions per second, a rate of 10^{18} ν's along one of the straight sections could be achieved**

  (M. Lindroos)

  - A new effort is on its way to re-visit the rare-earth region on the nuclear cart and measure the EC properties of possible candidates. The best: a half life of less than 1 min with an EC decay feeding one single nuclear level.

Physics Prospects

- Most important is to determine the full physics reach for oscillation physics with a monochromatic neutrino beam: it would allow to concentrate the intensity in the most interesting point (s) in E/L

... By fine tunning of the boosted neutrino energy

... By varying the baseline: Canfranc?, Frejus?,

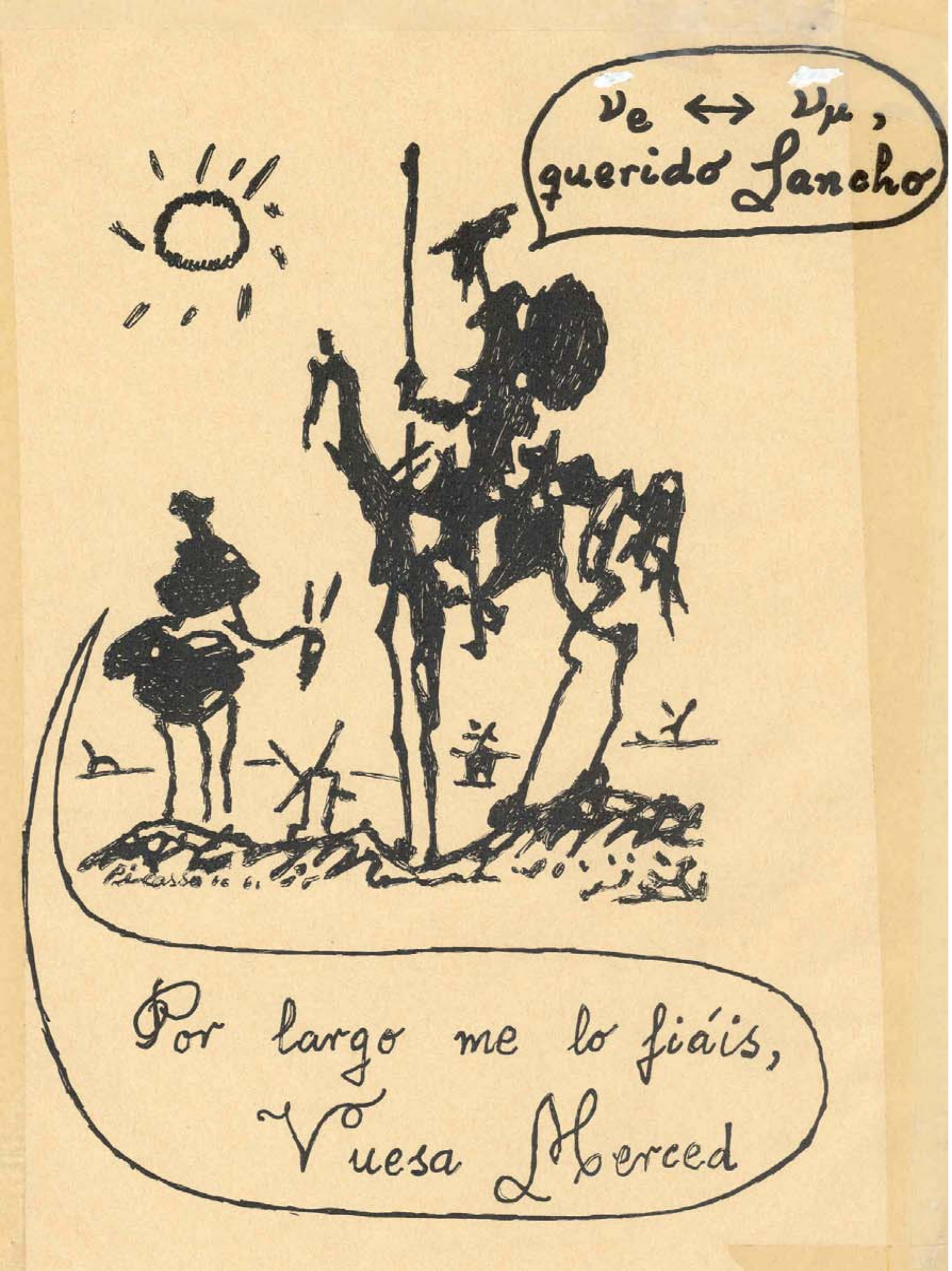
a combination of the two L's?

... By combining EC neutrinos with β^- antineutrinos from ^{6}He

.... Comments:

- In these conditions, experiment needs a counting rate detector of e's and μ's only

- Realistic simulation including systematics effects (1% ?) in the disappearance rate



TWO COMPLEMENTARY

VISIONS OF THE WORLD

Thanks to my collaborators:

J. Burguet-Castell
C. Espinoza
M. Lindroos