Searching for CP violation in the neutrino sector (Romance con Lagunas)

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Second Part

Outline (I)

- Primer Romance
  - The invention and discovery of neutrinos
- Primera Laguna
  - Neutrino sources
- Segundo Romance
  - The anomalous particle
- Segunda Laguna
  - Neutrino detectors

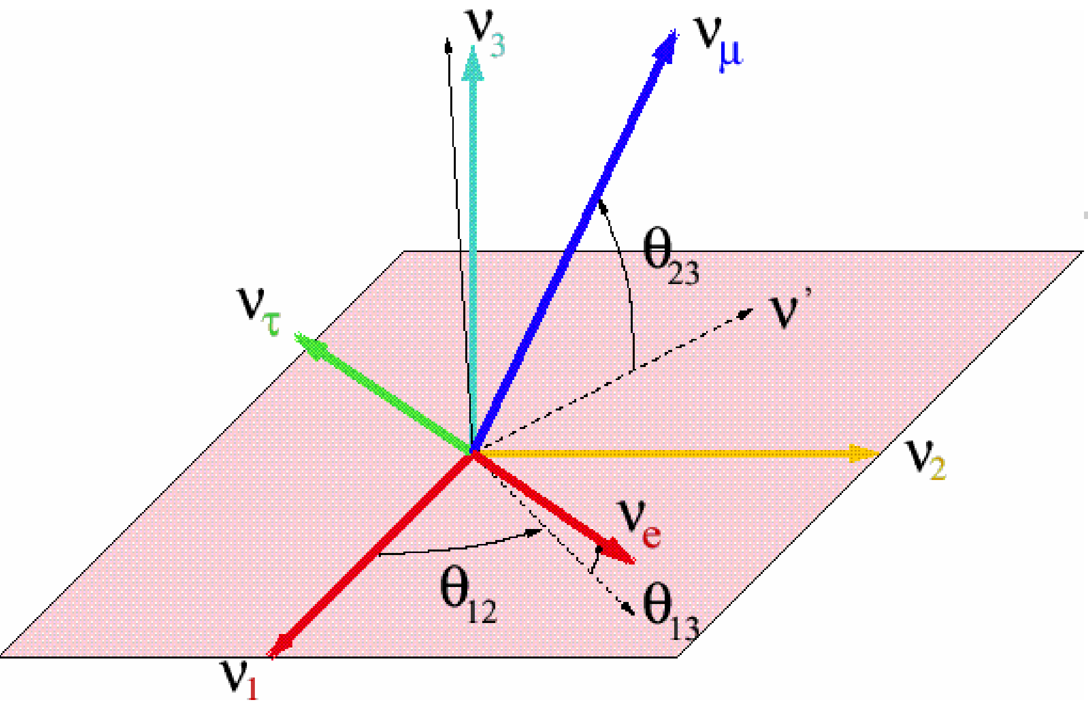
Outline (II)

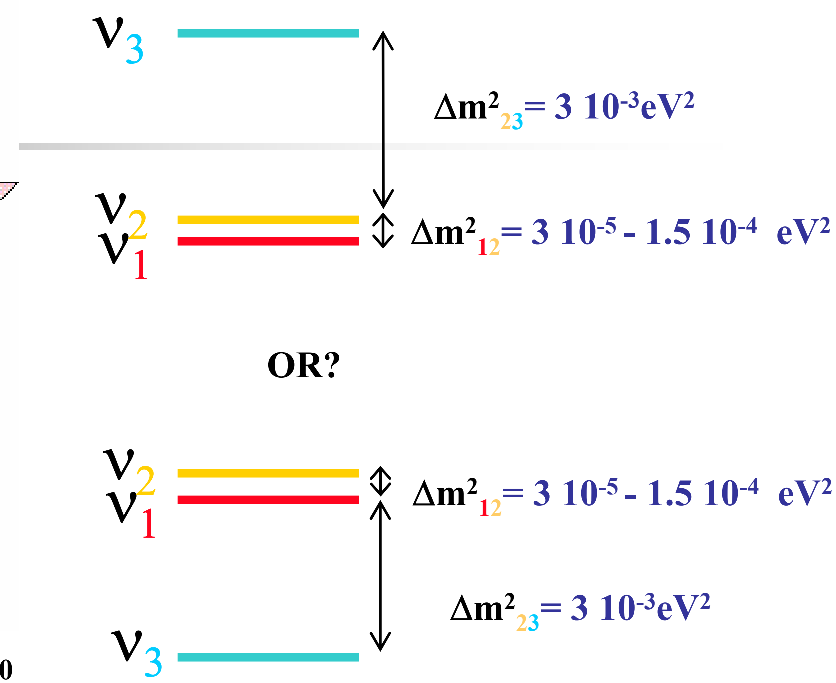
- Tercer Romance
  - The discovery of neutrino oscillations
- Tercera Laguna
  - Current experiments
- Cuarto Romance
  - The quest for the grial
- Cuarta Laguna
  - A Road to Lothlorien
- Ultimo Romance
  - Combining it all and a view of the future
- Ultima Laguna. The Unicorn

Cuarto Romance

- The quest for the grial
  - CP violation in neutrino oscillations

Neutrino mixing





θ_{23} (atmospheric) = 45^0 , θ_{12} (solar) = 30^0 , θ_{13} (Chooz) < 13^0

$$U_{MNS}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

Unknown or poorly known even after approved program:
θ_{13} , phase δ , sign of Δm^2_{13}

Present and Future

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

For three neutrinos:

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Maki-Nakagawa-Sakata-Pontecorvo matrix

(Double β Decay)

$$= \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & e^{i\alpha_3/2+i\delta} \end{pmatrix}$$

Solar,Reactor	Atmospheric	CP Violating Phase	Reactor, Accel.	Majorana Phases
		Future	Future	Future

$where\ c_{ij} = \cos\theta_{ij},\ and\ s_{ij} = \sin\theta_{ij}$

CP violation in ν oscillations

Vacuum oscillations $\left(W_{\alpha\beta}^{jk} \equiv [U_{\alpha j} U_{\beta j}^* U_{\alpha k}^* U_{\beta k}] \right)$

$$P(\nu_\alpha \rightarrow \nu_\beta) = -4 \sum_{k>j} \mathrm{Re}[\mathrm{W}_{\alpha\beta}^{\mathrm{jk}}] \sin^2 \left(\frac{\Delta \mathrm{m}_{\mathrm{jk}}^2 \mathrm{L}}{4 \mathrm{E}_\nu} \right)$$

$$\pm \quad 2 \sum_{k>j} \mathrm{Im}[\mathrm{W}_{\alpha\beta}^{\mathrm{jk}}] \sin \left(\frac{\Delta \mathrm{m}_{\mathrm{jk}}^2 \mathrm{L}}{2 \mathrm{E}_\nu} \right)$$

Observability of CP-violation $\leftrightarrow$ measurable CP-asymmetries:

$$A_{\alpha\beta}^{CP} \equiv \frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)} = \frac{2 \sin\delta c_{13} \sin 2\theta_{13} \overbrace{\sin 2\theta_{12} \frac{\Delta m_{12}^2 L}{4E_\nu}}^{\text{solar}} \overbrace{\sin 2\theta_{23} \sin^2 \frac{\Delta m_{13}^2 L}{4E_\nu}}^{atmos}}{P_{\nu_\alpha \nu_\beta}^{\text{CP}-\text{even}}}$$

- Two locks to CP-violation: LMA solution ($\surd$), $\theta_{13} \geq 0$ (?)
- Largest at $E/L \sim \Delta m_{atmos}^2$ and for subleading transitions $\nu_e \rightarrow \nu_\mu / \nu_\tau$

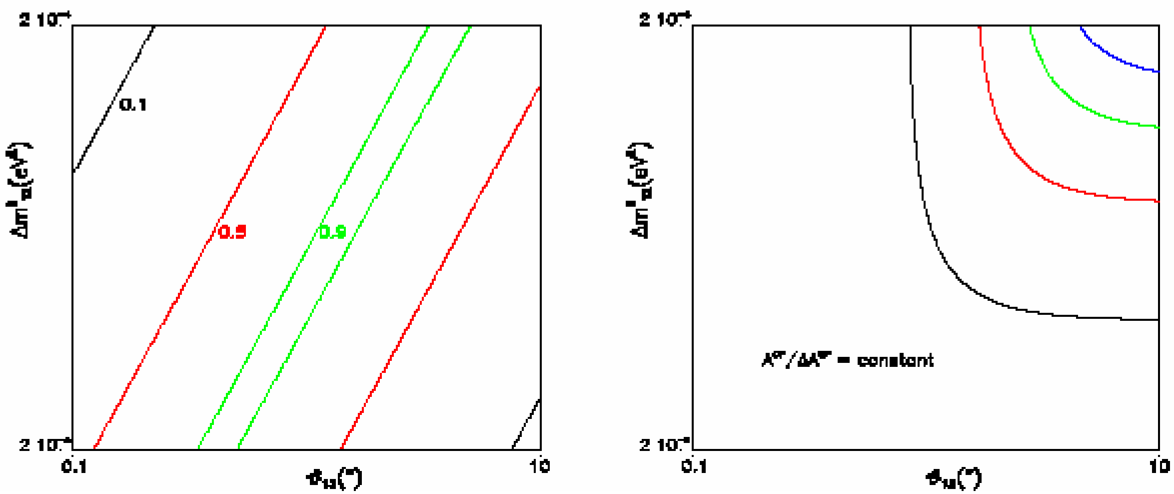
$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{23} L}{2}\right) \equiv P^{atmos}$$

$$+ \quad c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12} L}{2}\right) \equiv P^{solar}$$

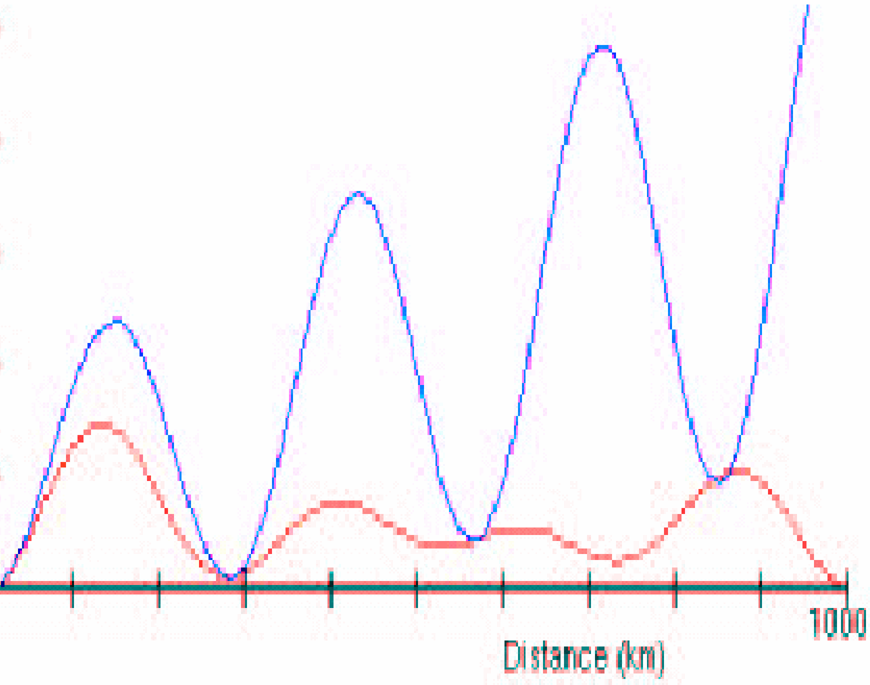
$$+\tilde{J} \quad \cos\left(\pm\delta - \frac{\Delta_{23} L}{2}\right) \frac{\Delta_{12} L}{2} \sin\left(\frac{\Delta_{23} L}{2}\right) \equiv P^{inter}$$

$$\left(\tilde{J} \equiv c_{13} \ \sin 2\theta_{13} \ \sin 2\theta_{12} \ \sin 2\theta_{23}, \quad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu}\right)$$

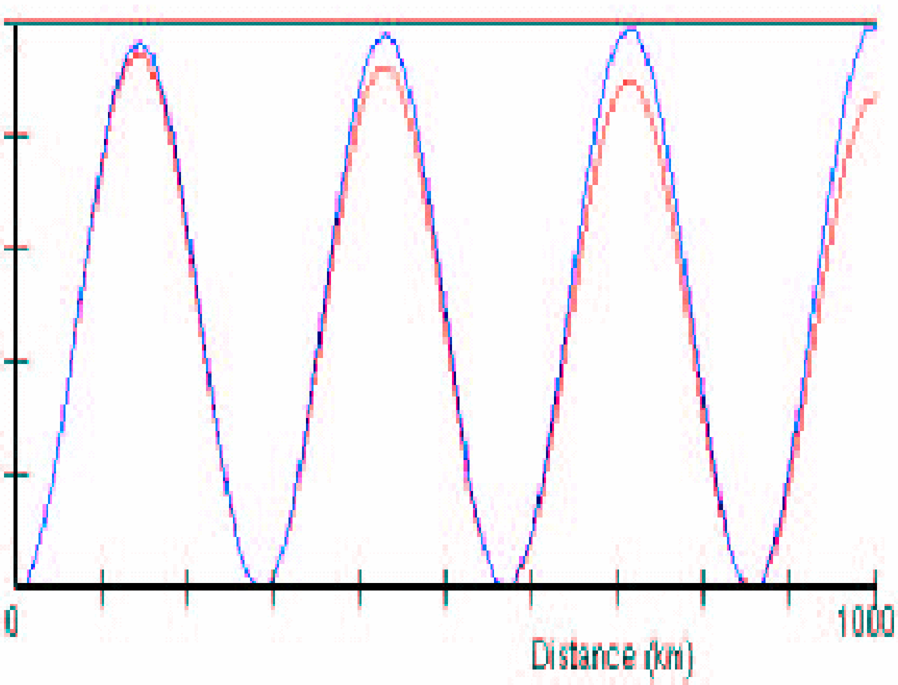
A. Cervera et al



$P_{\nu_e \to \nu_\mu}$ vs. $P_{\bar{\nu}_e \to \bar{\nu}_\mu}$



$P_{\nu_\mu \to \nu_\tau}$ vs. $P_{\bar{\nu}_\mu \to \bar{\tau}_\mu}$



$E_\nu = 500$ MeV $\theta_{13} = 8^\circ$ $\delta = 90^\circ$

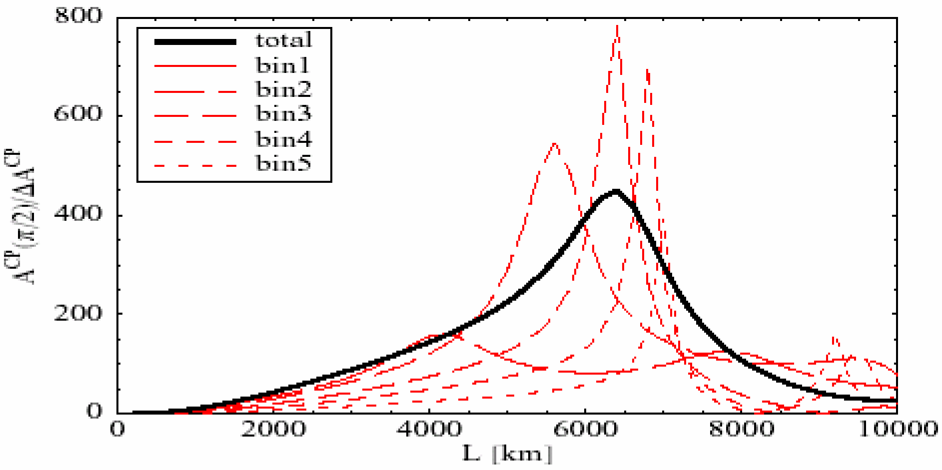
Spectrum

The same long-baseline experiments to measure θ_{13}, δ can measure sign(Δm^2_{13}) , because neutrino propagation in the Earth gets modified by coherent forward scattering on electrons: $\pm \rightarrow \nu/\bar{\nu}$ *Wolfenstein, Mikheyev,Smirnov*

$$|\Delta m^2_{13}| \quad \Rightarrow \quad |\Delta m^2_{13} \pm 2\sqrt{2} G_F N_e E_\nu|$$

$$\sin^2 2\theta_{13} \quad \Rightarrow \quad \sin^2 2\theta_{13} \left(\frac{\Delta m^2_{13}}{\Delta m^2_{13} \pm 2\sqrt{2} G_F N_e E_\nu} \right)^2$$

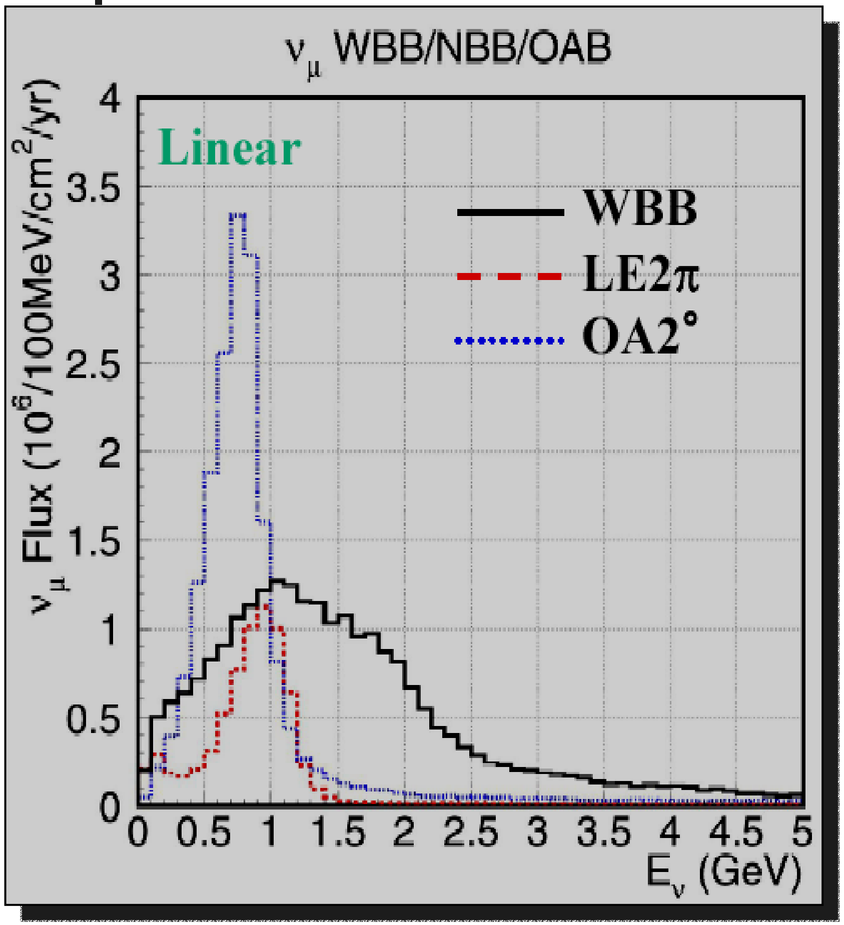
For $E_\nu \sim O(10)$GeV $\rightarrow$ large amplification/suppression of $P_{\nu_e \rightarrow \nu_\mu}$ depending on the sign(Δm^2_{13})



Cuarta Laguna

- The Road to Lothlorien
  - Super Beams
  - Beta Beams
  - Neutrino Factories

JHF Super Beam



Off-axis kinematics

$$p_L = \gamma(p^* \cos\Theta^* + \beta p^*)$$
$$p_T = p^* \sin\Theta^* \,,$$

$$\Theta = \frac{R}{L} = \frac{1}{\gamma}\frac{\sin\Theta^*}{1+\cos\Theta^*} \,,$$

$$E_\nu(R) = \frac{2\gamma p^*}{1+(\gamma\frac{R}{L})^2}$$

$$\Phi_\nu(R) = \frac{\frac{\gamma^2}{\pi L^2}}{(1+(\gamma\frac{R}{L})^2)^2} \,,$$

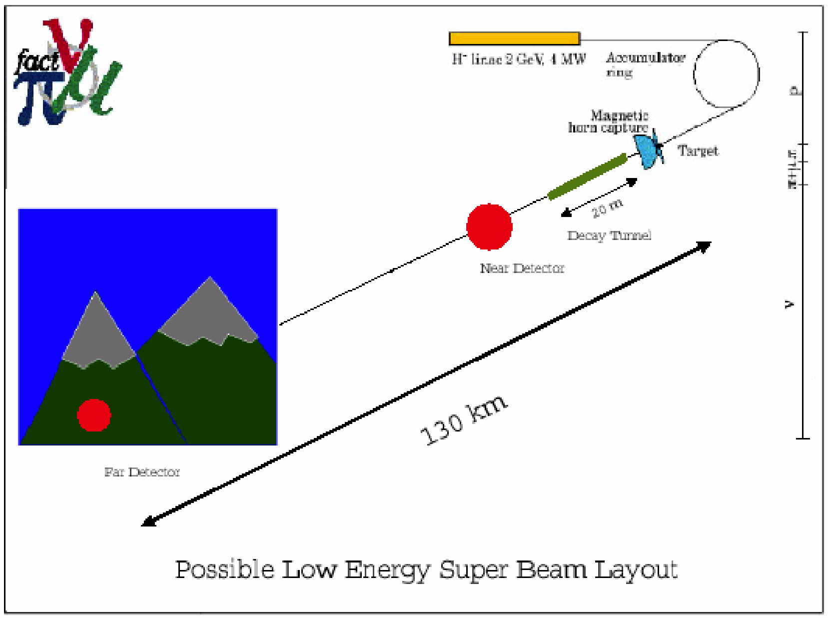
The decisive feature is:

$$\frac{\partial E_\nu}{\partial \gamma} = 0$$

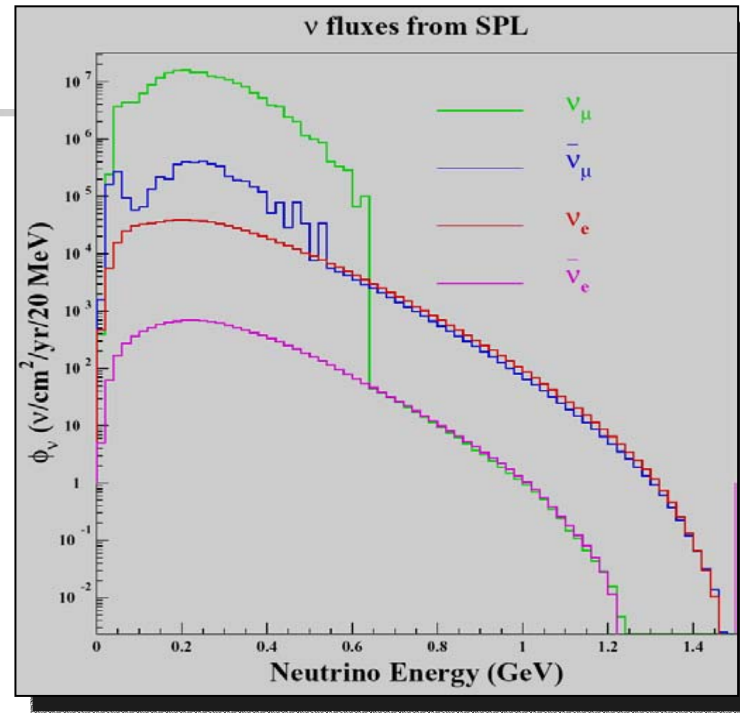
at the 'magic' angle

$$\Theta = 1/\gamma \,.$$

The SPL Super-Beam



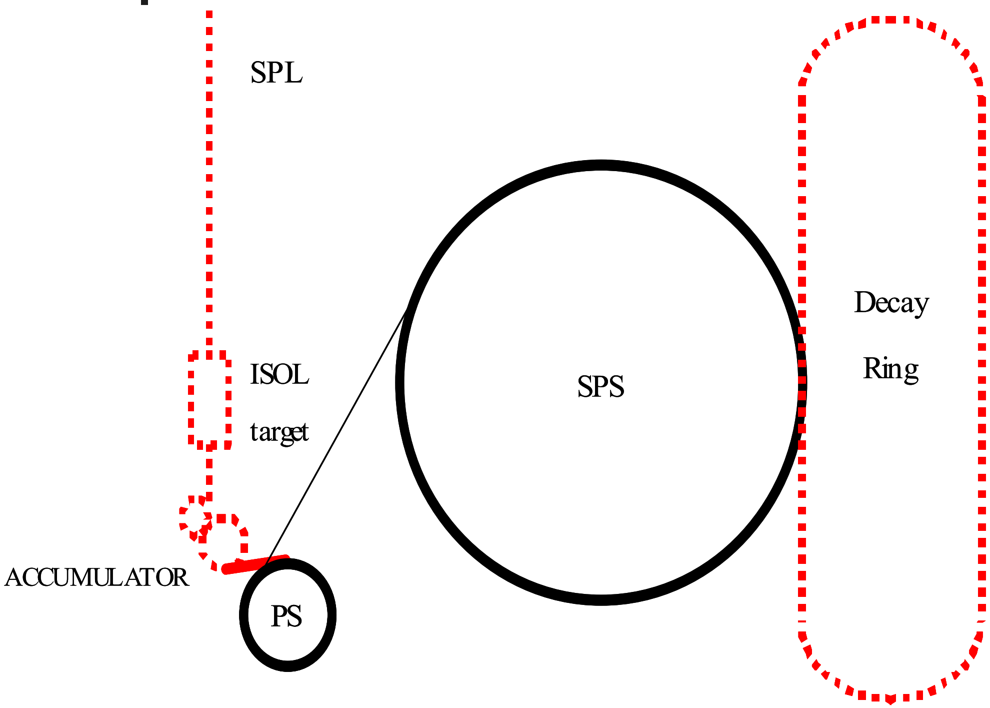
M. Mezzetto, "SuperBeam studies at CERN", *Nufact 01*, Tsukuba, May 24-30, 2001 3

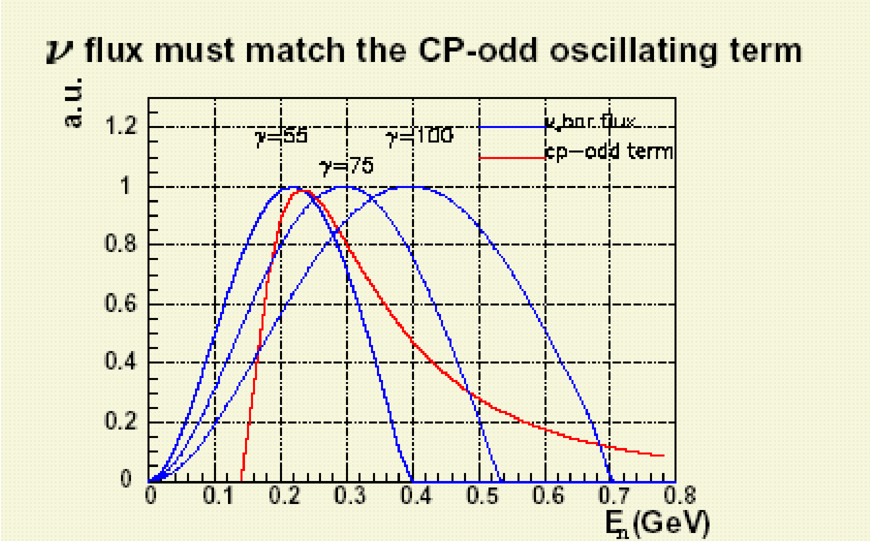


- Base line : CERN to FREJUS
- Megaton water detector
- O(10) years?

- Low energy beams (~ 250 MeV)
- 4 (8, 10… 20?) MW

Beta Beam

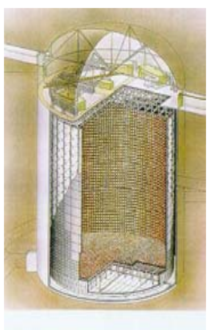

SPL
ISOL
target
ACCUMULATOR
PS
SPS
Decay
Ring

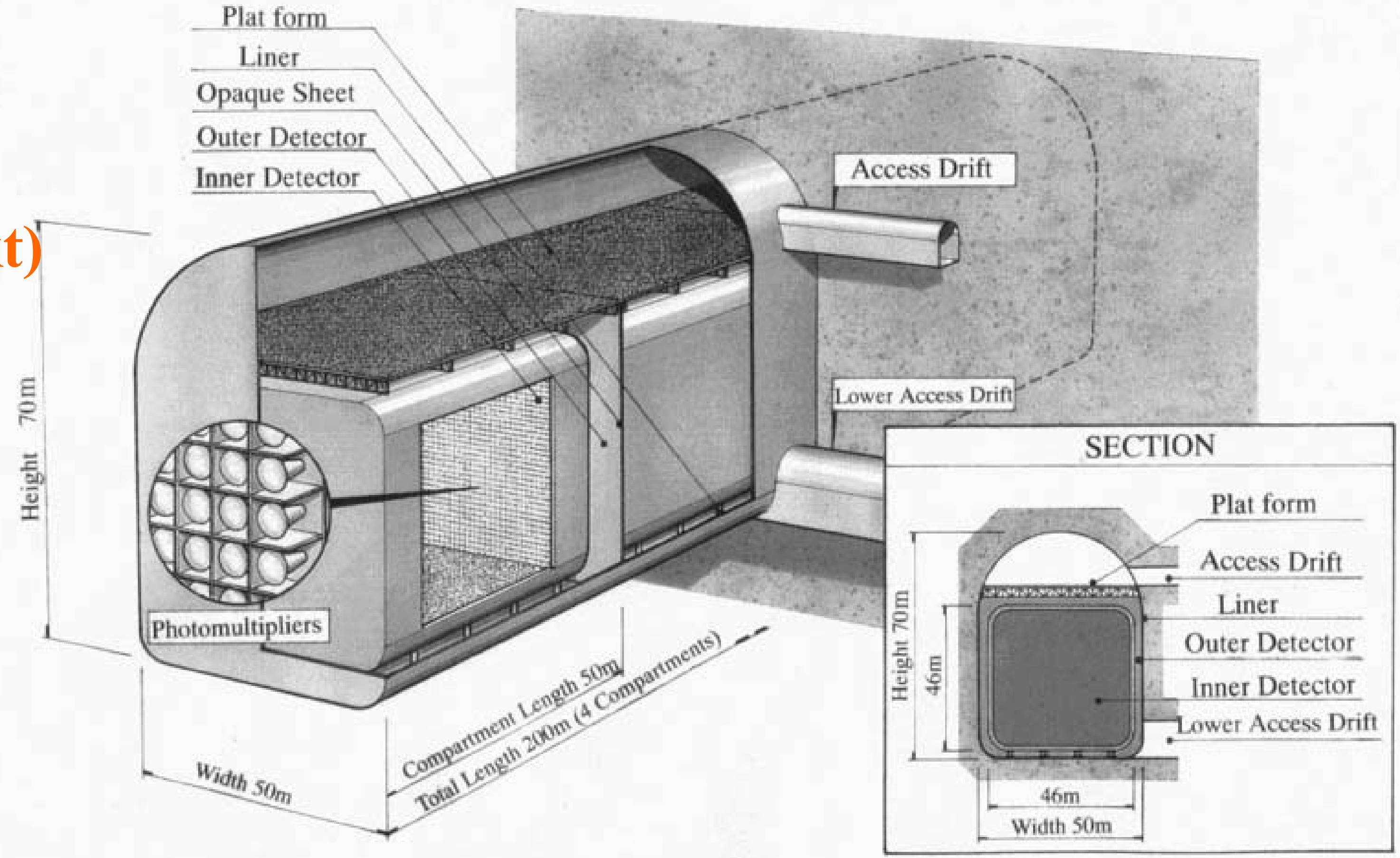

ν flux must match the CP-odd oscillating term
a.u.
γ=55
γ=75
γ=100
ν bar flux
cp−odd term
1.2
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
E (GeV)

Megaton Water Detector

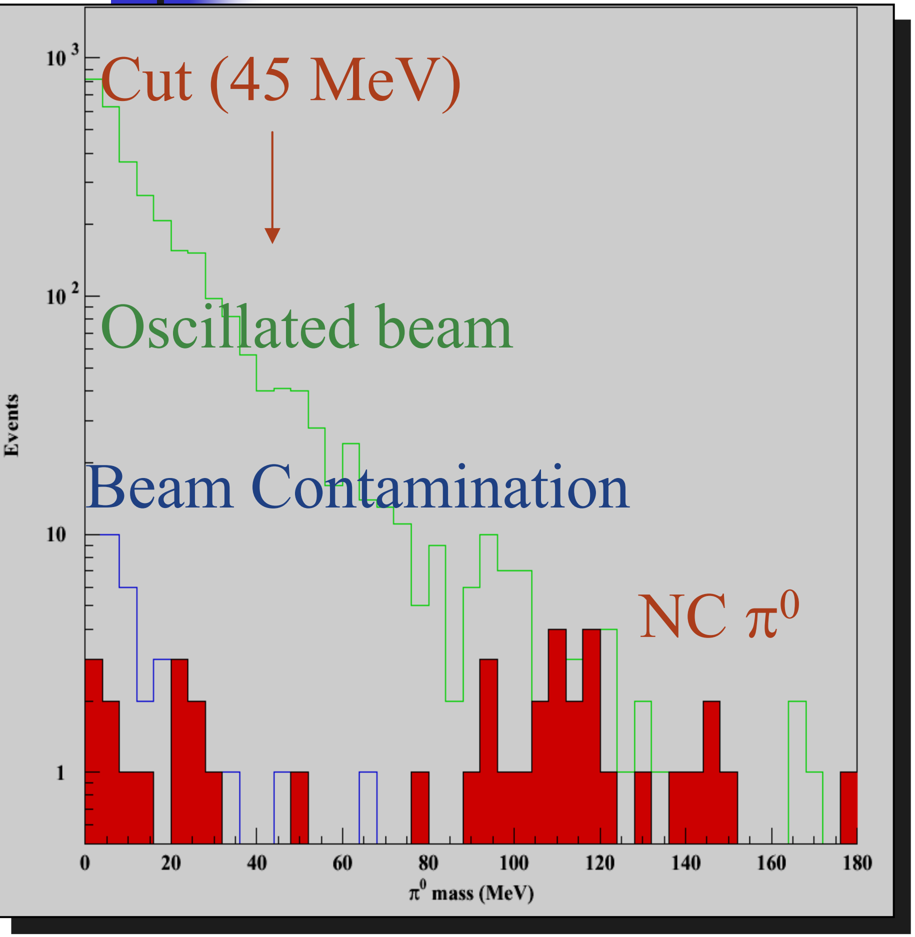
Example: Hyper-K
1,000 kt

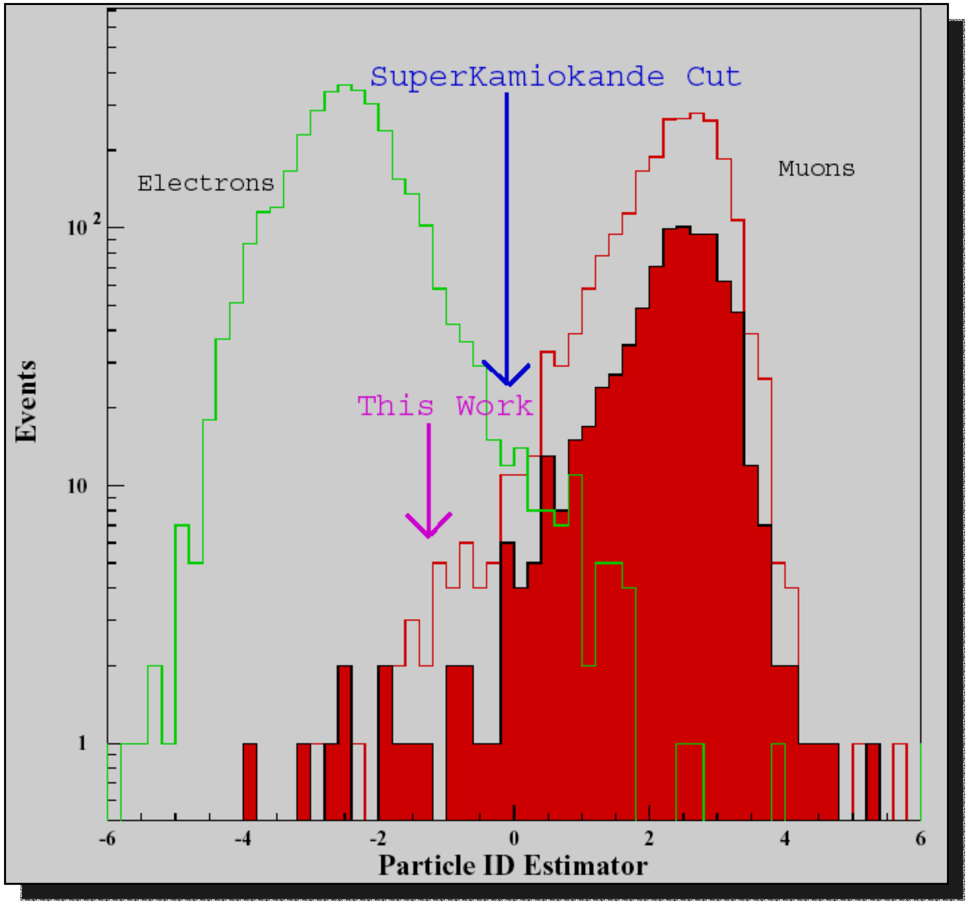
Super-K
22.5kt (50kt)





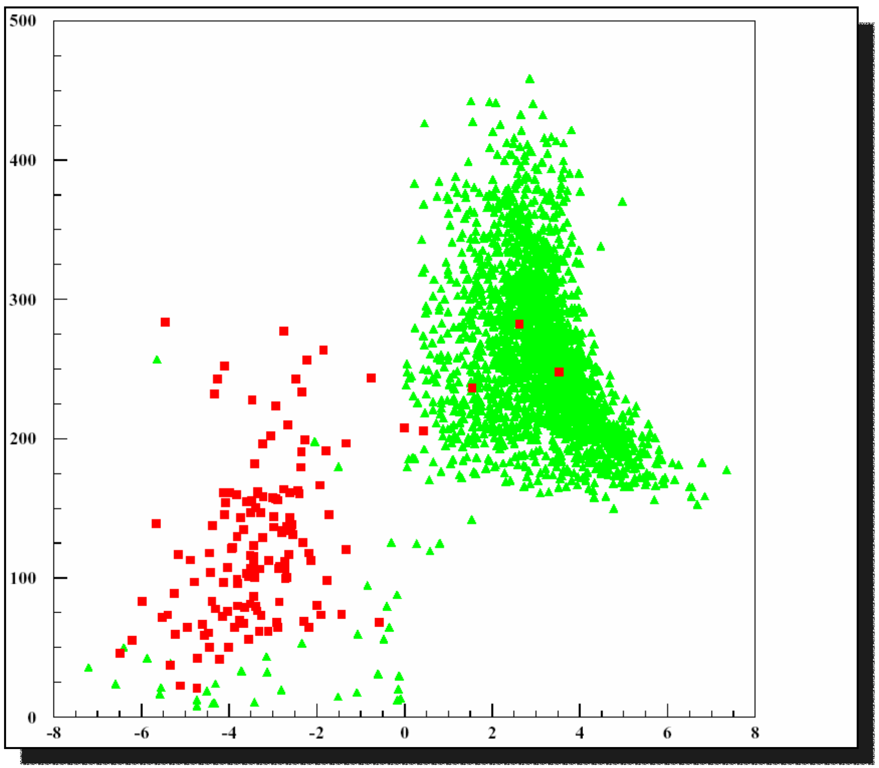
Control of backgrounds (SPL)

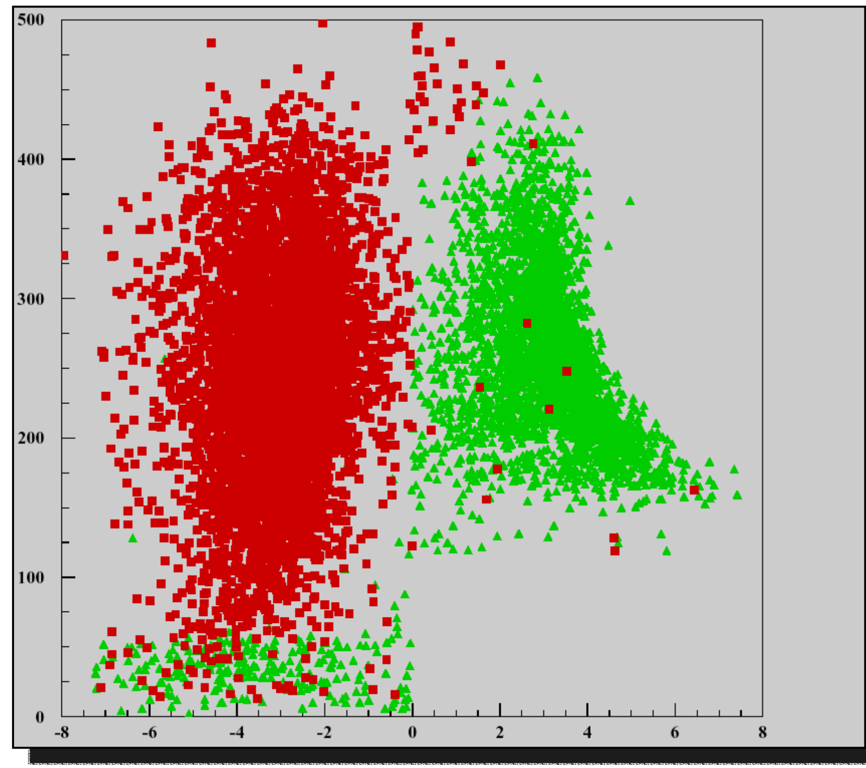




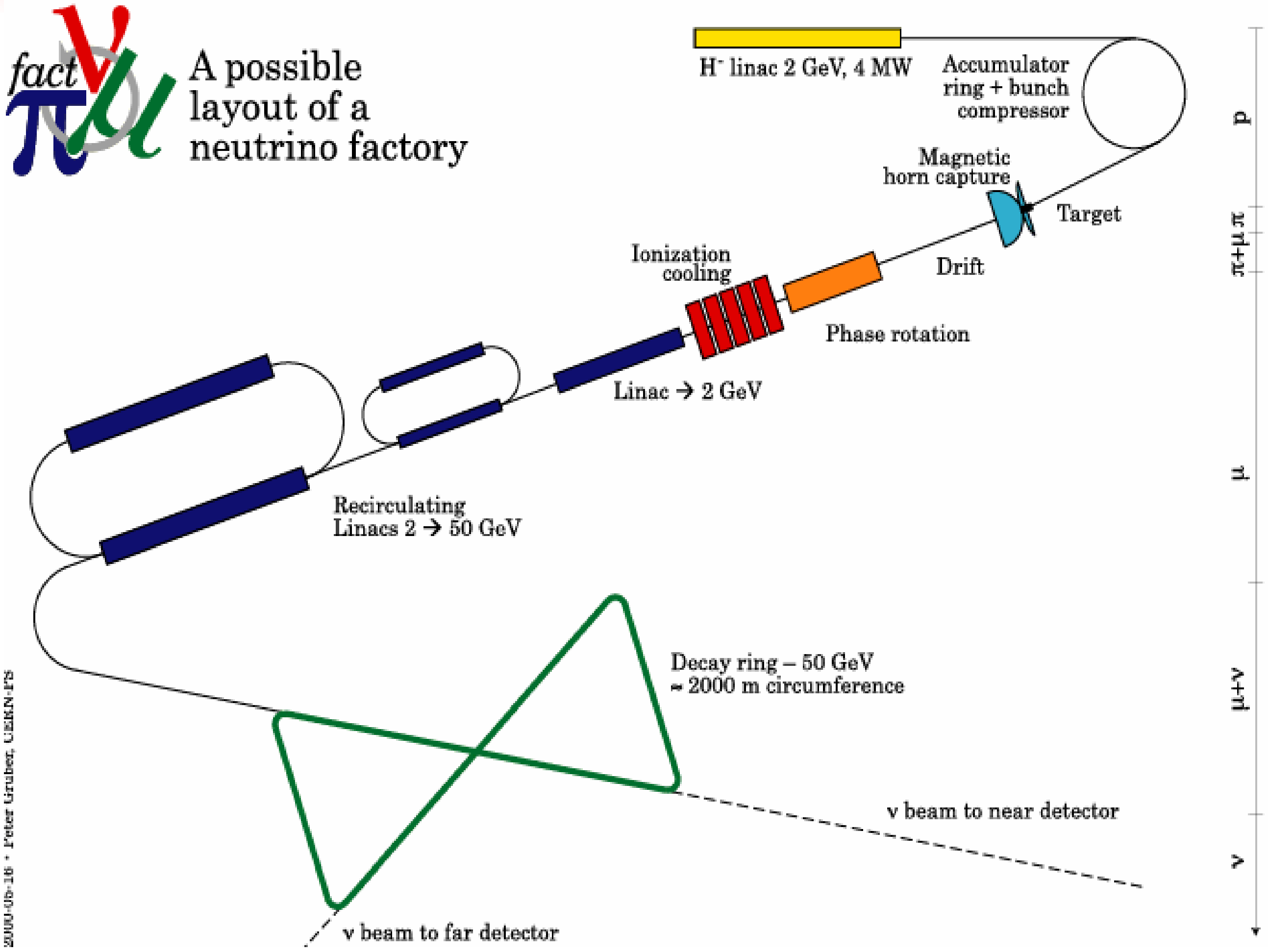
Beta Beam

E-like Bkgd　　Mu-like Signal





Neutrino Factory



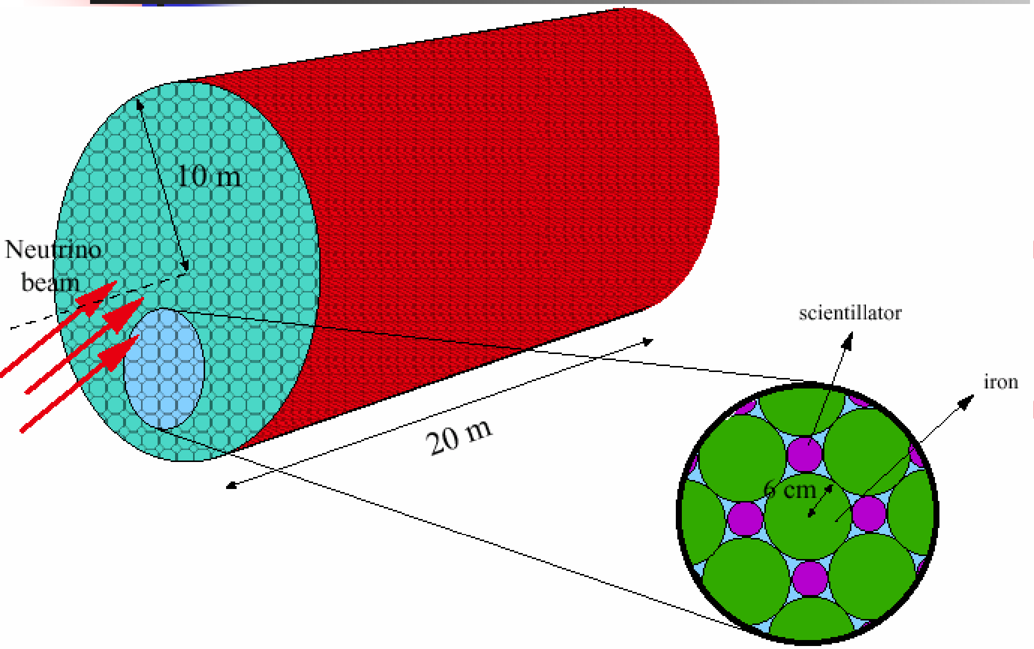
- Very high intensity:

  10^{21} ν/yr
- Muon energy

  30-50 GeV
- Two beams
- 3000 Km

  1000 (7000) km
- 15 years from now? (neutrino business = paticence)

« Golden » signature : wrong sign muons



$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$\bar{\nu}_\mu + N \longrightarrow \mu^+ + X$$ CC

right sign muon

$$\bar{\nu}_\mu + N \longrightarrow \bar{\nu}_\mu + X$$ NC

$$\nu_e \overset{\text{osc}}{\sim} \nu_\mu$$

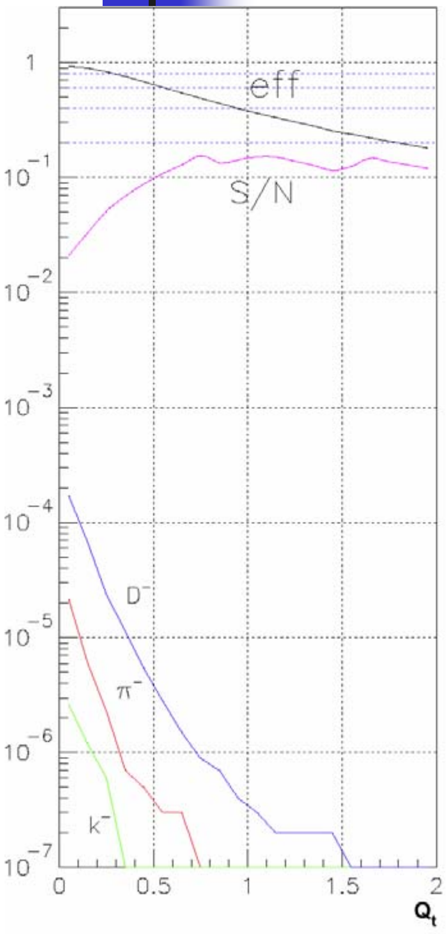
$$\nu_\mu + N \longrightarrow \mu^- + X$$ SIGNAL

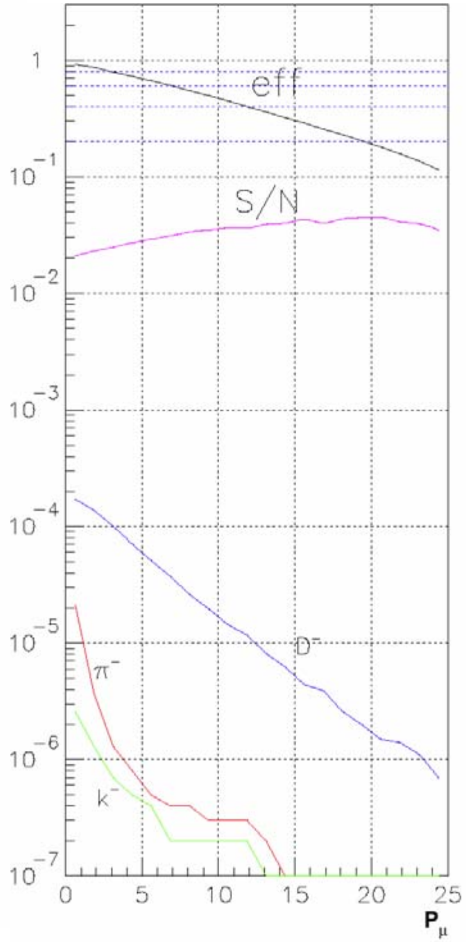
wrong sign muon

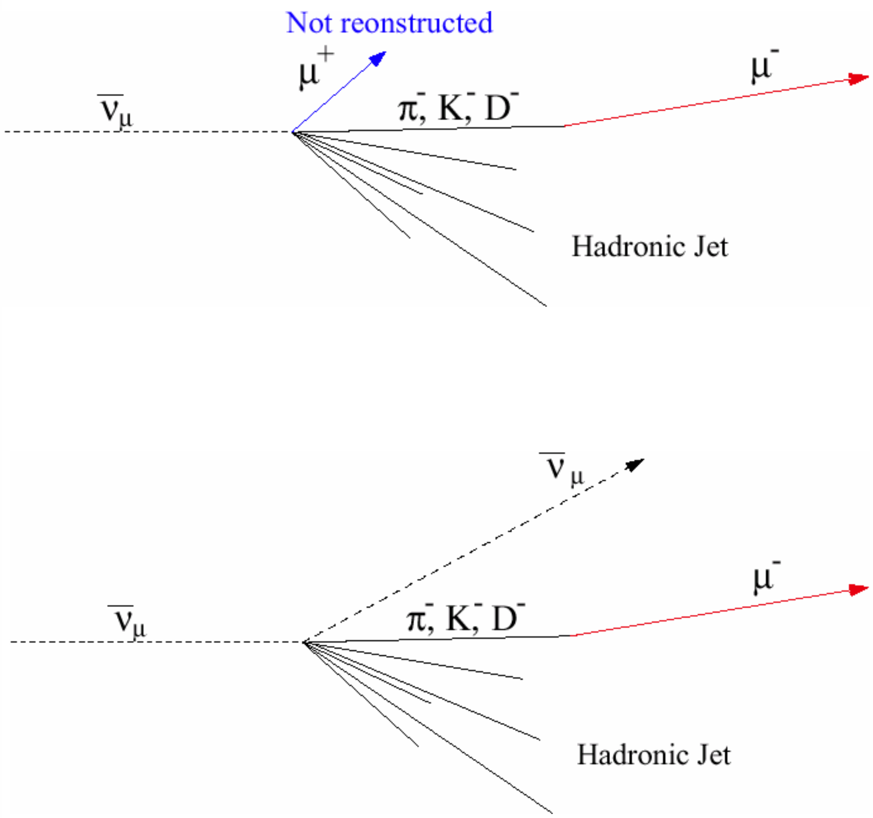
Very massive calorimeter (50-100 kton)

Good identification of muon charge

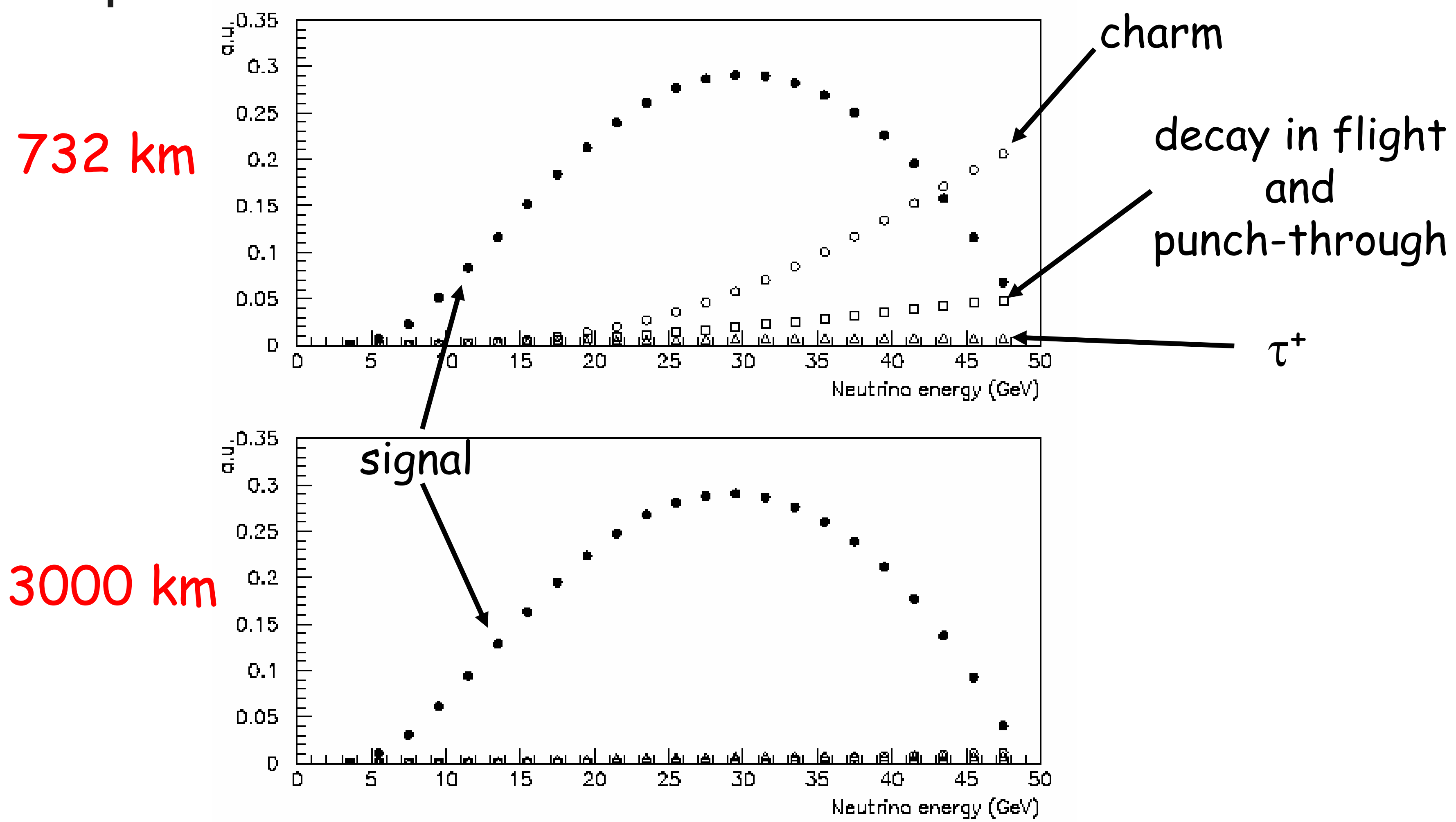
Signal and backgrounds







Signal & background vs E_ν



Ultimo Romance

- Degeneracies and the way to solve them
  - Degeneracies
  - Combining base lines
  - Combining facilities
  - Combining golden and silver channels
  - Combine it all!

Oscillation Probability

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{23} L}{2}\right) \equiv P^{atmos}$$

$$+ \quad c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12} L}{2}\right) \equiv P^{solar}$$

$$+\tilde{J} \quad \cos\left(\pm\delta - \frac{\Delta_{23} L}{2}\right) \frac{\Delta_{12} L}{2} \sin\left(\frac{\Delta_{23} L}{2}\right) \equiv P^{inter}$$

$$(\tilde{J} \equiv c_{13} \ \sin 2\theta_{13} \ \sin 2\theta_{12} \ \sin 2\theta_{23}, \quad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu})$$

A. Cervera *et al*

Oscillation Probability

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

$$(+\ \text{neutrinos},\ -\ \text{antineutrinos}) \quad \begin{cases} X_{\pm} = \Delta_{atm}^2 \times f_X^{\pm}(\theta_{23}, A, L) \\ Y_{\pm} = \Delta_{sun} \times \Delta_{atm} \times f_Y^{\pm}(\theta_{12}, \theta_{23}, A, L) \\ Z = \Delta_{sun}^2 \times f_Z(\theta_{12}, \theta_{23}, A, L) \end{cases}$$

(θ'_{13}, δ') are fake solutions of:

$$\left.\begin{array}{l} P_{\nu_e\nu_\mu}(\theta'_{13}, \delta') = P_{\nu_e\nu_\mu}(\theta_{13}, \delta) \\ P_{\bar{\nu}_e\bar{\nu}_\mu}(\theta'_{13}, \delta') = P_{\bar{\nu}_e\bar{\nu}_\mu}(\theta_{13}, \delta) \end{array}\right\} \text{at fixed } E_\nu \text{ and } L.$$

They appear when the full parameter is considered and the energy dependence of the signal (including realistic backgrounds and efficiencies) is not strong enough.

In fact, 3 sources of degeneracies

Intrinsic $\rightarrow$ $P(\theta'_{13}, \delta') = P(\theta_{13}, \delta)$

(J. Burguet-Castell, *et al*, Nucl. Phys. **B608**, (2001))

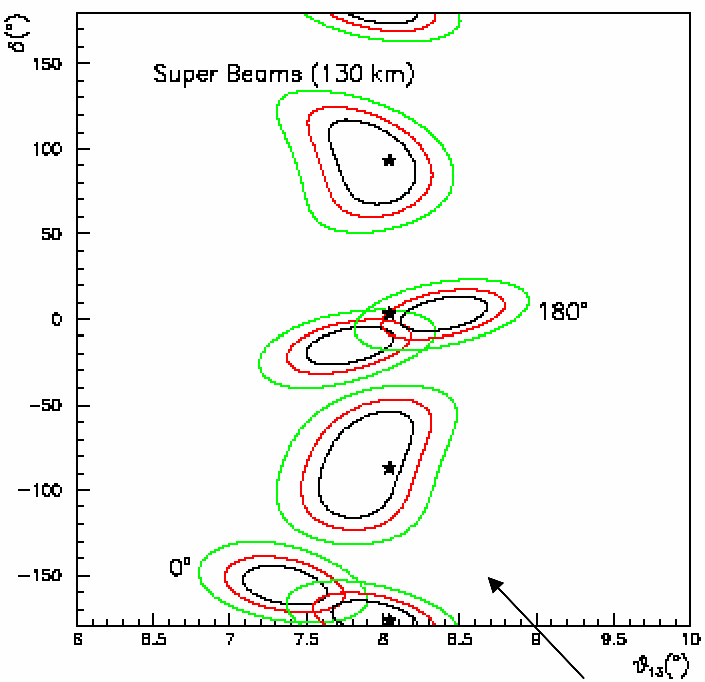
θ_{23}**- Octant** $\rightarrow$ $P(\theta'_{13}, \delta', \frac{\pi}{2} - \theta_{23}) = P(\theta_{13}, \delta)$

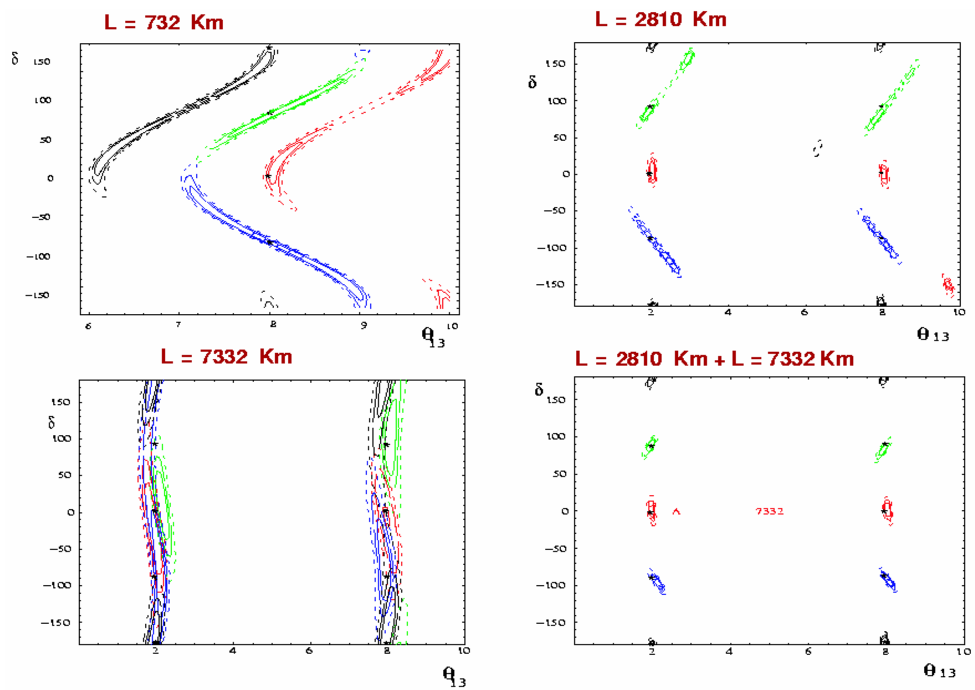
(G.L. Fogli and E. Lisi, Phys. Rev. **D54** (1996); V. Barger *et al*, Phys. Rev. **D65** (2002).)

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

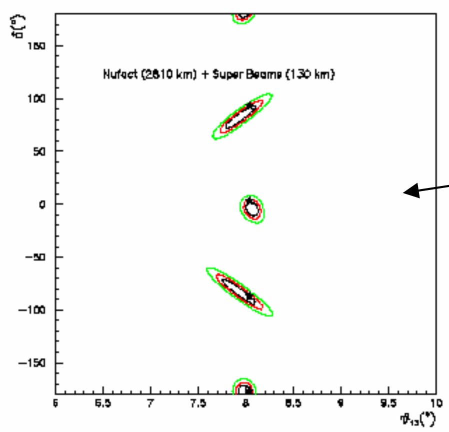
(H. Minakata and H. Nunokawa, JHEP **0110** (2001); V. Barger *et al*, Phys. Rev. **D65** (2002).)

Degeneracies

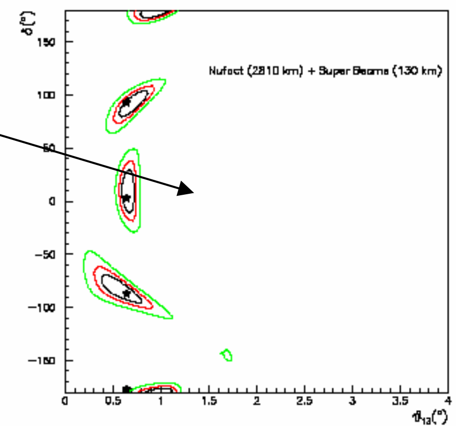


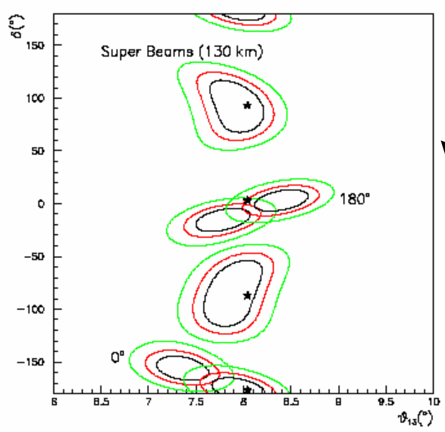


Solving intrinsic degeneracy combining two facilities



Combination of SB + NF





Intrinsic degeneracy

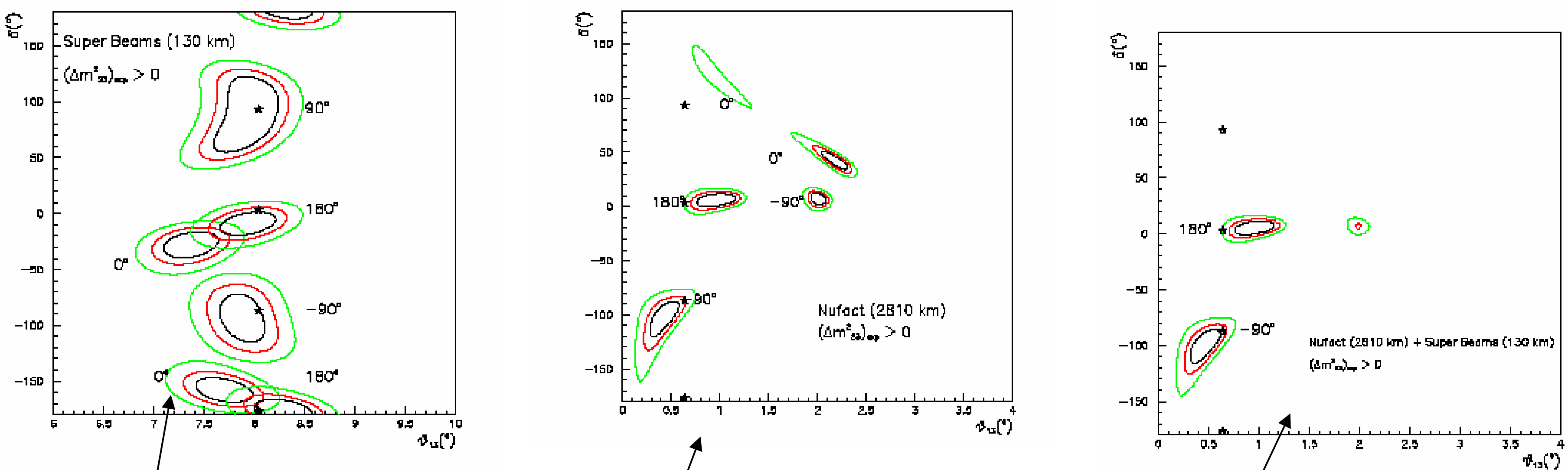
SB alone

4 Jul 2002

Superbeams plus Neutrino Factory: the golden path to leptonic CP violation

J. Burguet-Castell[a], M.B. Gavela[b,1], J.J. Gómez-Cadenas[a,c2], P. Hernández[c,3], O. Mena[b,4]

Solving sign Degeneracy combining two facilities

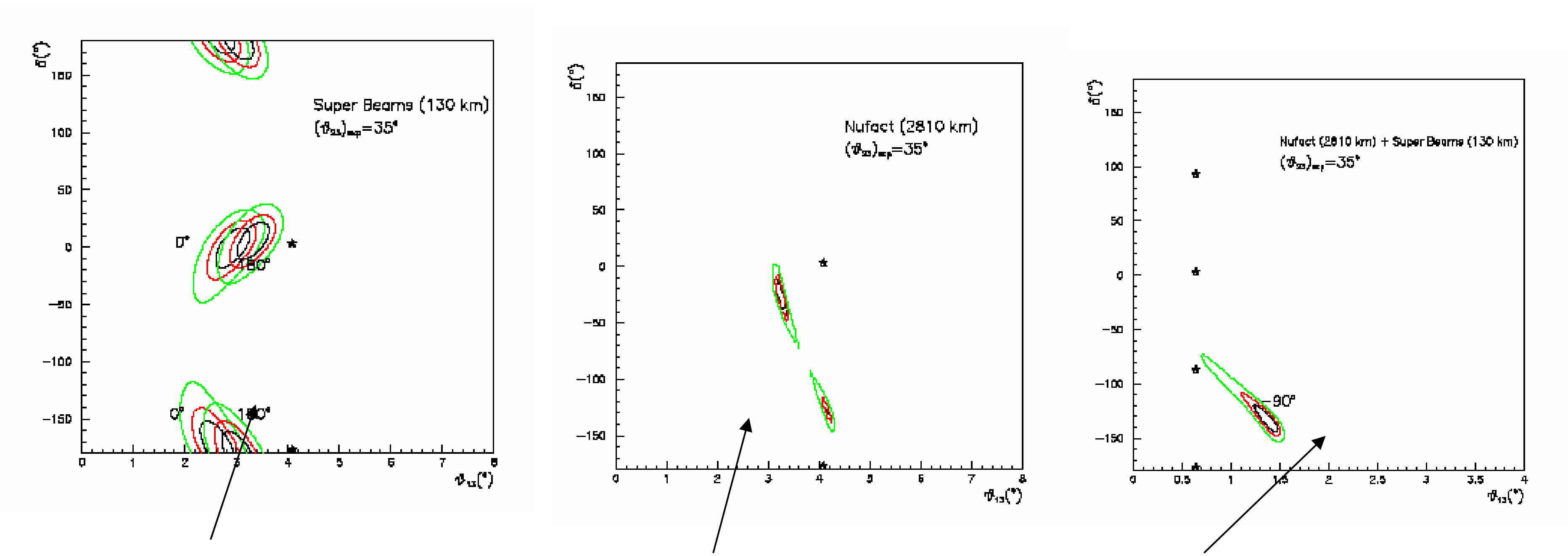


Super Beam

Nufact

Combination

Solving θ_{23} Degeneracy combining two facilities



Super Beam

NuFact

Combination

The silver channel at the Neutrino Factory

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

$$(+\ \text{neutrinos},\ -\ \text{antineutrinos}) \begin{cases} X_{\pm}^{\tau} & = & \Delta_{atm}^2 \times (c_{23}^2/s_{23}^2) f_X^{\pm}(\theta_{23}, A, L) \\ Y_{\pm} & = & \Delta_{sun} \times \Delta_{atm} \times f_Y^{\pm}(\theta_{12}, \theta_{23}, A, L) \\ Z^{\tau} & = & \Delta_{sun}^2 \times (s_{23}^2/c_{23}^2) f_Z(\theta_{12}, \theta_{23}, A, L) \end{cases}$$

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

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

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)

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

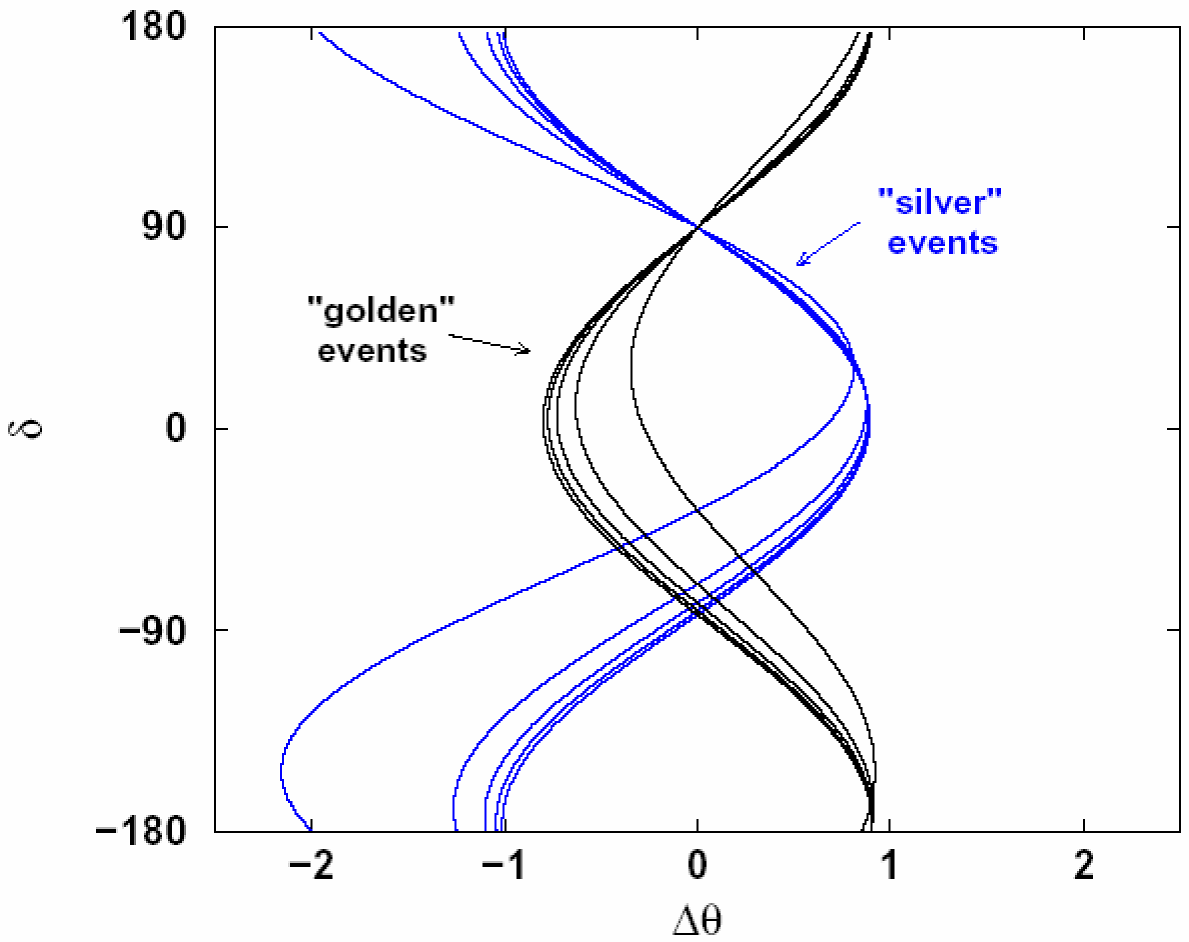
$$\begin{aligned} P^{\pm}_{e\tau} = \; & X^{\tau}_\pm \sin^2(2\,\theta_{13}) \\ & - Y_\pm \cos\left(\delta \mp \frac{\Delta_{atm} L}{2}\right) \cos\theta_{13} \sin(2\,\theta_{13}) \\ & + Z^{\tau} + \dots \end{aligned}$$

with

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

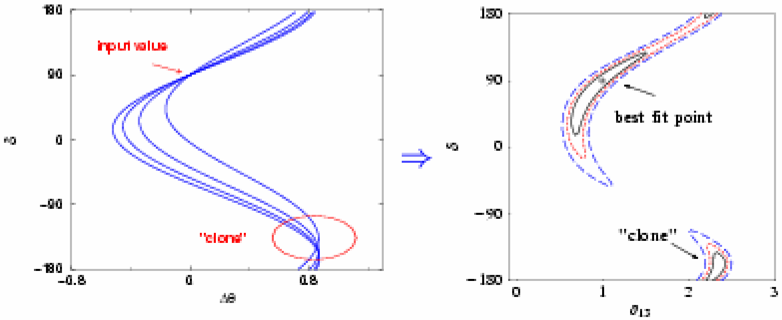
(+ neutrinos, − antineutrinos)

Golden vs silver events

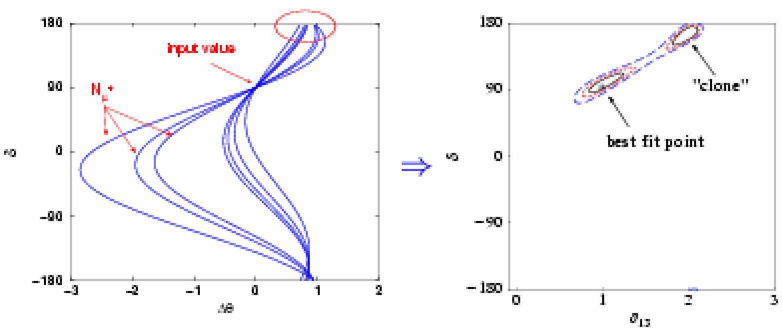


Results for golden muons at $L = 3000$ Km

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



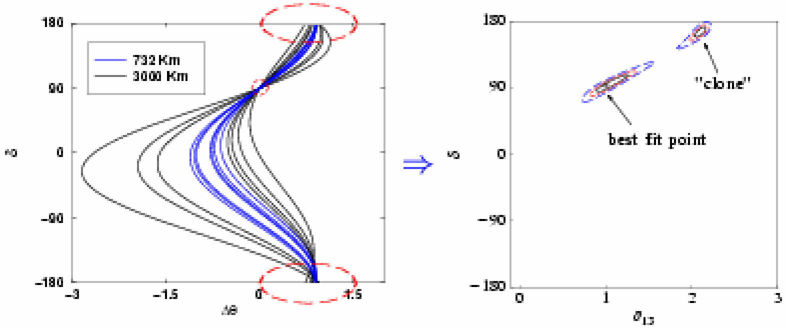
Ten years of data taking: two polarities
(μ^+ and μ^- in the storage ring)



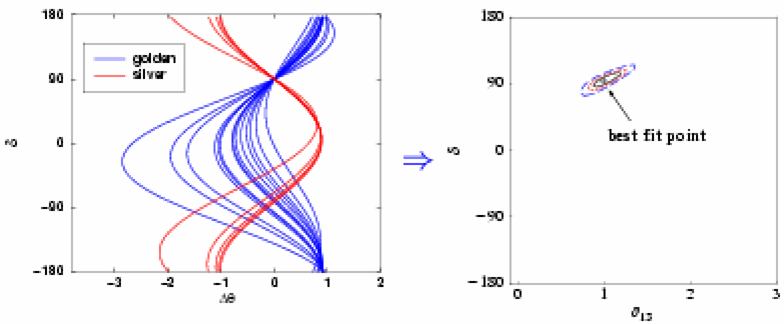
Input parameters: $\bar{\theta}_{13} = 1^\circ, \bar{\delta} = 90^\circ$

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)

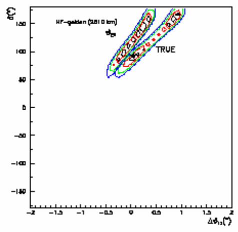


Input parameters: $\bar{\theta}_{13} = 1^\circ, \bar{\delta} = 90^\circ$

One detector

Consider the NuFact golden channel:
best option for one detector, with baseline $L = 2810$
(no sign degeneracies for $\theta_{13} \geq 1°$).

- 40 Kton MID

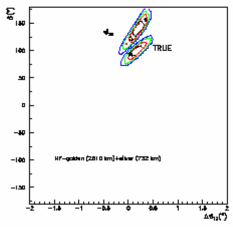


$\bar{\theta}_{13} = 2° \; \bar{\delta} = 90°$

Two detectors

You can now add a second detector.
We can take advantage of the NuFact silver channel...

- 40 Kton MID
- 4 Kton ECC

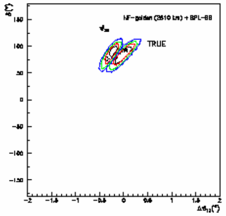


$\bar{\theta}_{13} = 2° \; \bar{\delta} = 90°$

Two detectors

... or of the Superbeam-driven water Cherenkov.

- 40 Kton MID
- 400 Kton WC

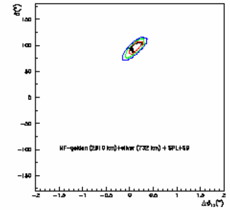


$\bar{\theta}_{13} = 2° \; \bar{\delta} = 90°$

The Three Detectors

However, the very best possibility is
to combine the three detectors in their FULL GLORY.

- 40 Kton MID
- 4 Kton ECC
- 400 Kton WC



$\bar{\theta}_{13} = 2° \; \bar{\delta} = 90°$

Ultima Laguna. The unicorn

Oh this beast is the one that never was.
They didn't know that; unconcerned, they had
Loved its grace, its walk, and how it stood
Looking at them, calmly, with clear eyes.
It hadn't been. But from their love, a pure beast arose.
It raised its head and hardly needed to exist.
They fed it, not with any grain,
But always just with the thought that
It might be

Rainer Maria Rilke, The sonnets to Orpheus