ν oscillation physics from a MWatt proton source

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Introduction

ν are the most elusive particles of the MSM:

$$m_\nu \simeq 0, \;\; Q_{em} = 0, \;\; Q_{color} = 0, \;\; Q_{SU(2)\times U(1)/U(1)_{em}} \neq 0$$

Nevertheless they have provided essential information on the two most striking features of the fermionic content of the SM:

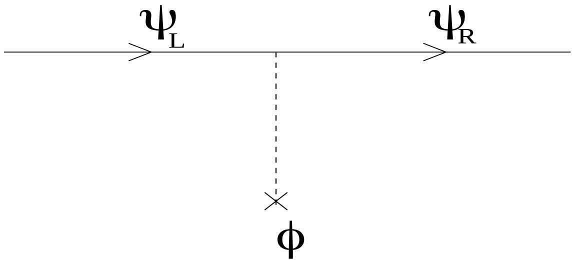
- Left-handedness of the weak interactions
- The family structure: $N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_{\nu\bar{\nu}}} = 2.984 \pm 0.008$

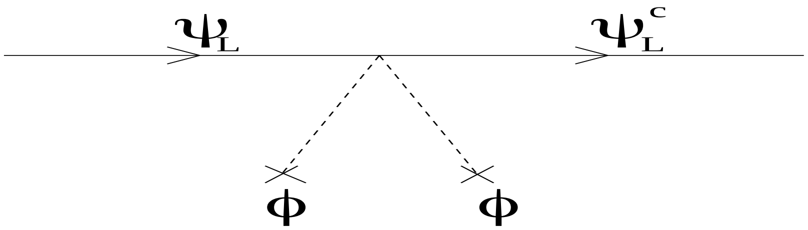
The impressive ν-experiments of recent years have revealed that they have a tiny mass:

- A new hierarchy in the flavour sector ? A new physics scale ?

Neutrino masses

In the SM fermion masses originate in the interaction with the Higgs field:





$$\lambda_\nu \, \bar{\psi}_R \, \Phi \, \psi_L + h.c. \qquad \frac{\alpha_\nu}{M} \nu_L^T C \, \tilde{\Phi}^T \, \tilde{\Phi} \, \nu_L + h.c.$$

$$m_f = \lambda_f \, v \qquad m_\nu = \alpha_\nu \frac{v^2}{M}$$

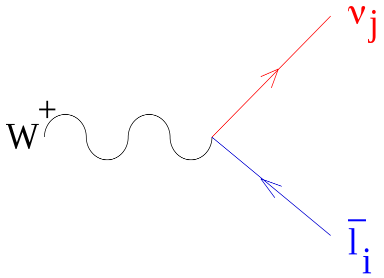
$$L \qquad \not{L}$$

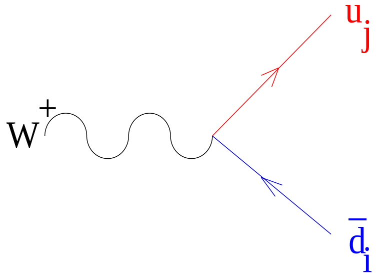
A new physics scale, M, can explain the new hierarchy (if $\sim M_{GUT}$) and other misteries of the flavour sector and is associated to the breaking of the a global symmetry of the SM: total lepton number L !

Neutrino masses and mixing

If the fermions have a mass the charged current interactions are not flavour diagonal: there is mixing among the families

$$\frac{g}{\sqrt{2}} W^+_\mu \sum_{ij} \left(V^{ij}_{NMS} \overline{l^i_L} \gamma_\mu \nu^j_L + V^{ij}_{CKM} \overline{U^i_L} \gamma_\mu D^j_L \right) + h.c.$$





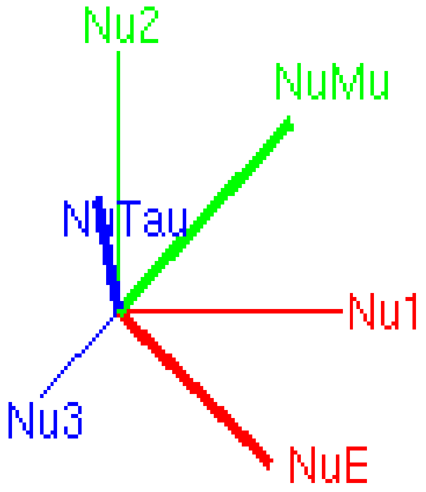
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V_{NMS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The NMS matrix has four physical parameters:

	Angles	Phases
Dirac	3	1
Majorana	3	3

$$V_{NMS}^{\text{Dirac}} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12}e^{i\delta} & 0 \\ -s_{12}e^{i\delta} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$V_{MNS}^{\text{Majorana}} = V_{MNS}(\theta_{12}, \theta_{13}, \theta_{23}, \delta) \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$



More homework than discover the Higgs to complete the SM!

ν-masses are not just the last fundamental parameters in the SM to add to the Particle Data Book...

- If they are Majorana they provide a window into a new physics scale which might give us a clue on the origin of fermion masses (flavour sector):
  $\{\lambda_f\} \rightarrow 22/26$ parameters of the SM

why 3 families ? why is there a hierarchy between them ?

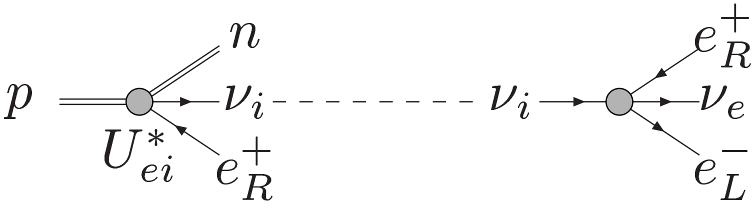
- Lepton number violation provides a simple mechanism to explain the observed baryon asymmetry in the Universe → leptogenesis

- Big Bang nucleosynthesis is very sensitive to the number of light neutrino species

- they contribute to the energy density of the Universe (→ dark matter, large scale structure...)

Neutrino oscillations

Pontecorvo



Neutrinos produced in a flavour eigenstate can change flavour as they propagate:

$$x = 0 \quad |\nu_\alpha\rangle = \sum_j V_{\alpha j} |\nu_j\rangle \Rightarrow \quad |\nu_\alpha(x)\rangle = \sum_j V_{\alpha j}\ e^{iEt}\ e^{ixp_j} |\nu_j\rangle$$

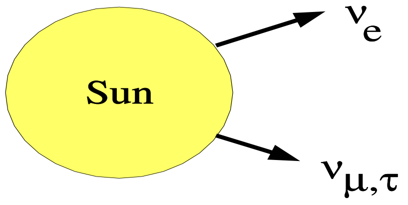
Vaccuum oscillations (2 families): $L_{\rm osc}(km) = 2\pi \frac{E_\nu(GeV)}{1.27\Delta m^2(eV^2)}$

$$P_{\alpha\beta} = \sin^2 2\theta\ \sin^2\left(\frac{\Delta m^2\, L}{4E_\nu}\right) \rightarrow \text{appearance}$$

$$P_{\alpha\alpha} = 1 - P_{\alpha\beta} < 1 \rightarrow \text{disappearance}$$

Solar ν oscillations

Many beautiful experiments (Homestake, Gallex, Sage, Kamiokande, SuperKamiokande, SNO) have shown that the Sun shines more ν_μ, ν_τ than ν_e:



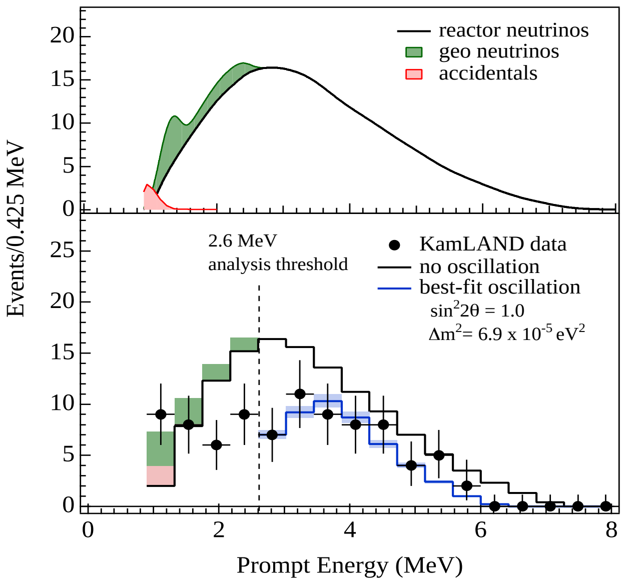
$$\phi_{^8B}^{SNO-CC}(\nu_e) = 1.76^{+0.06}_{-0.05}(\text{stat})^{+0.09}_{-0.09}(\text{syst}) \times 10^6 cm^{-2}s^{-1}$$

$$\phi_{^8B}^{SNO-NC}(\nu_{e,\mu,\tau}) = 5.09^{+0.44}_{-0.43}(\text{stat})^{+0.46}_{-0.43}(\text{syst}) \times 10^6 cm^{-2}s^{-1}$$

Confirmed by a reactor ν experiment: **KamLAND (2002)**

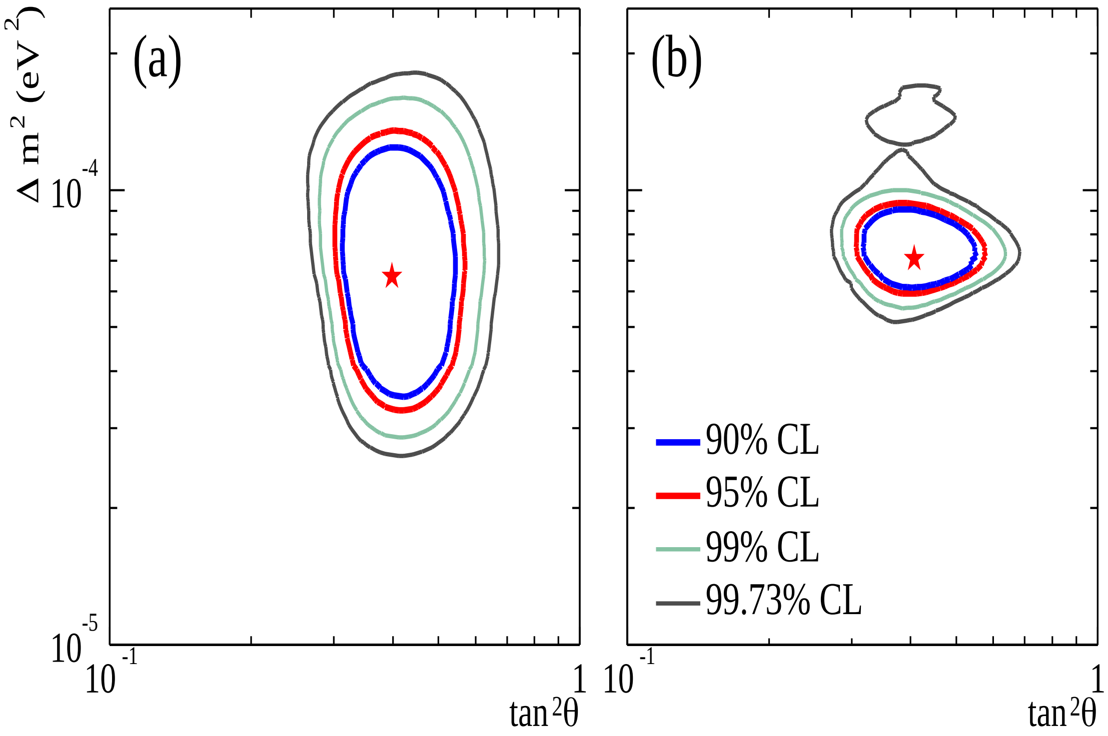
$\bar{\nu}_e$ disappearance

$\langle E_\nu(\text{MeV})\rangle / L(100km) \sim 10^{-5}\text{eV}^2$



Solar ν oscillations

Global fit to the $\nu_e(\bar{\nu}_e) \rightarrow \nu_x(\bar{\nu}_x)$ oscillation hypothesis

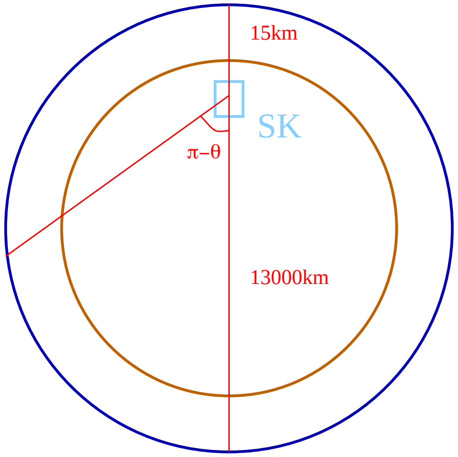


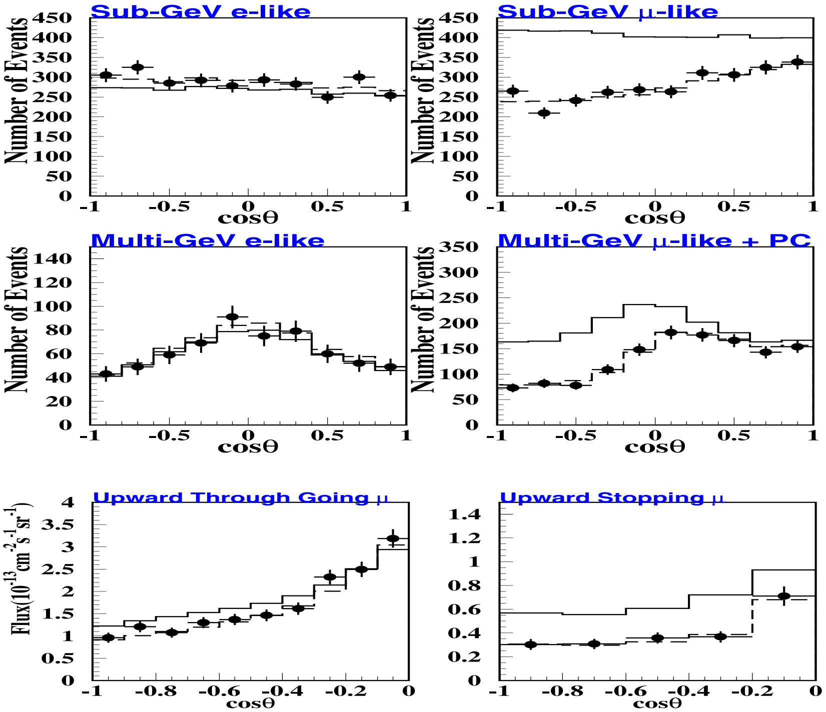
SNO coll. et al

$$\Delta m^2_{solar} = 7.1^{+1.0}_{-0.3} \cdot 10^{-5}\text{eV}^2 \qquad \theta_{solar} = 32.5^{\circ}{}^{+1.7}_{-1.6}$$

Atmospheric ν oscillations

SuperKamiokande (1998)





Less ν_μ than expected come from below

and a zenith angle dependence

compatible with the oscillation E/L

dependence

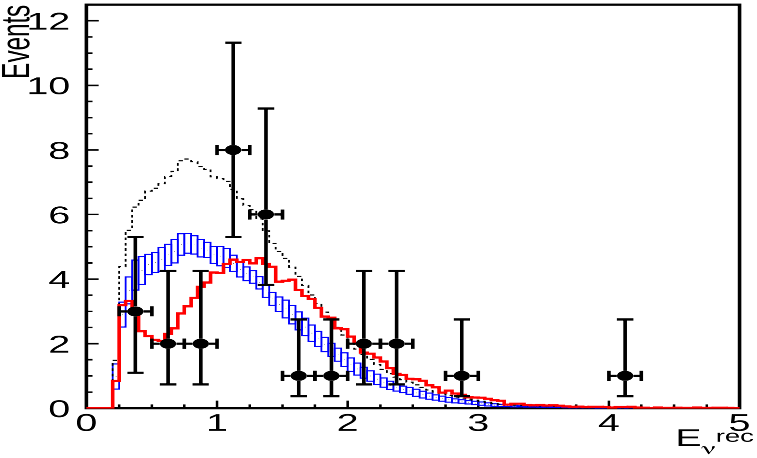
$$\nu_\mu(\bar{\nu}_\mu) \to \nu_\tau(\bar{\nu}_\tau)$$

Confirmation of the oscillation hypothesis in accelerator ν experiments

$$|\Delta m^2_{\rm atmos}| \sim \frac{E_\nu(1-10GeV)}{L(10^2-10^3km)}$$

Three such conventional beams KEK-Kamioka (235km), Fermilab-Soudan (730km), CERN-Gran Sasso (730km) will search for the disappearance of ν_μ or appearance of ν_τ:

K2K: $\sim 3\sigma$ evidence of ν_μ disappearance

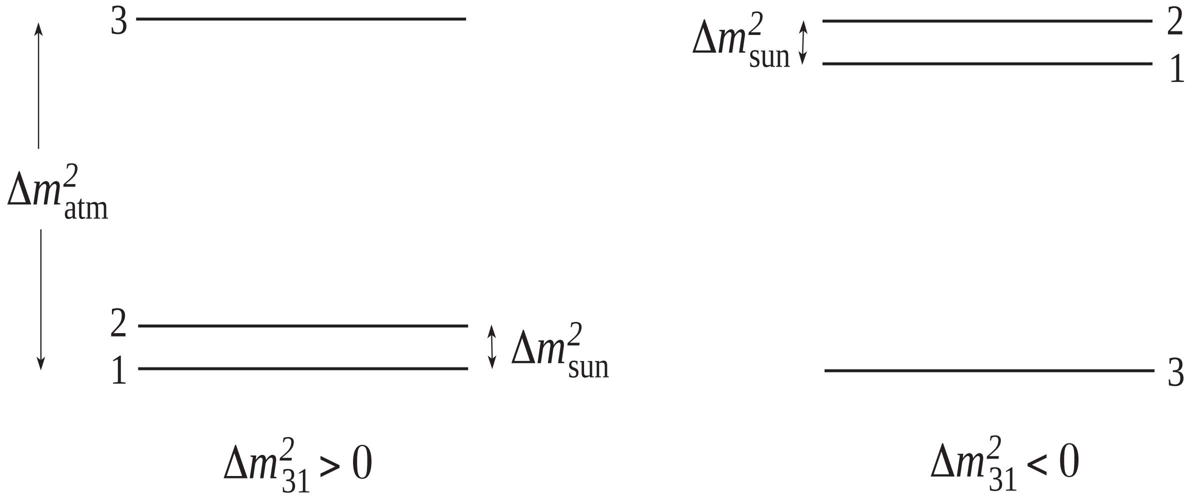


Combined analysis SK+K2K:

$$\Delta m^2_{atmos} = 2.6(4)\cdot 10^{-3}\text{eV}^2$$
$$0.75 < \tan^2\theta_{atmos} < 1.3$$

Atmos $\oplus$ Solar oscillations with 3 massive neutrinos

ν spectrum: $\Delta m^2_{23} = m^2_3 - m^2_2 = \Delta m^2_{atmos}$, $\Delta m^2_{12} = m^2_2 - m^2_1 = \Delta m^2_{solar}$



ν mixing matrix: $\oplus$ Chooz $\theta_{23} \to \theta_{\rm atmos}$, $\theta_{12} \to \theta_{\rm solar}$

$$V_{MNS} \simeq \begin{pmatrix} 0.84 & 0.54 & s_{13}e^{-i\delta} \\ -\frac{1}{\sqrt{2}}(0.54 + 0.84 s_{13}e^{i\delta}) & \frac{1}{\sqrt{2}}(0.84 - 0.54 s_{13}e^{i\delta}) & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}}(0.54 - 0.84 s_{13}e^{i\delta}) & -\frac{1}{\sqrt{2}}(0.84 + 0.54 s_{13}e^{i\delta}) & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

$\theta_{13} \leq 8^\circ$ $\quad \delta, \alpha_1, \alpha_2$ unconstrained

The homework

After the next generation of neutrino experiments we will probably be far from having the complete picture:

1. Measure better $(\Delta m^2_{23}, \theta_{23})$ and $(\Delta m^2_{12}, \theta_{12})$
   $\theta_{23} = \pi/4$ fundamental symmetry ?
2. Establish 3 family mixing: θ_{13}, δ
3. Establish if CP violation occurs: ie. $\sin\delta \neq 0$
4. Find the correct spectrum: ie. $\Delta m^2_{atmos} >$ or < 0

Precision ν osc. experiments $@\langle E_\nu \rangle / L \sim \Delta m^2_{atmos}$

5. Establish Majorananess and phases α_1, α_2
6. Find absolute ν mass scale ↔ new physics scale

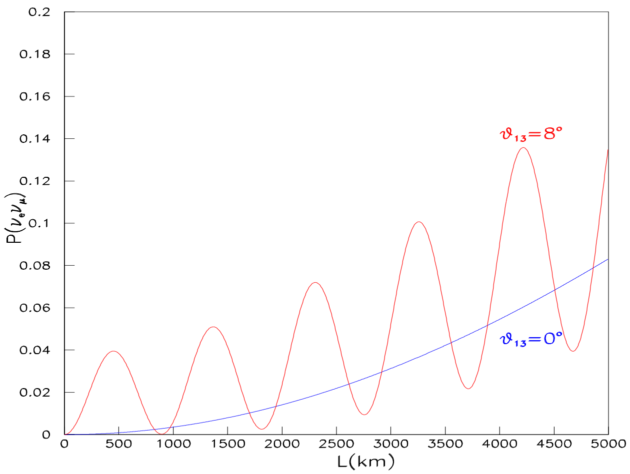
End-point of tritium β-decay
Rare $\not{L}$ violating decays: $0\nu\beta\beta$ decay

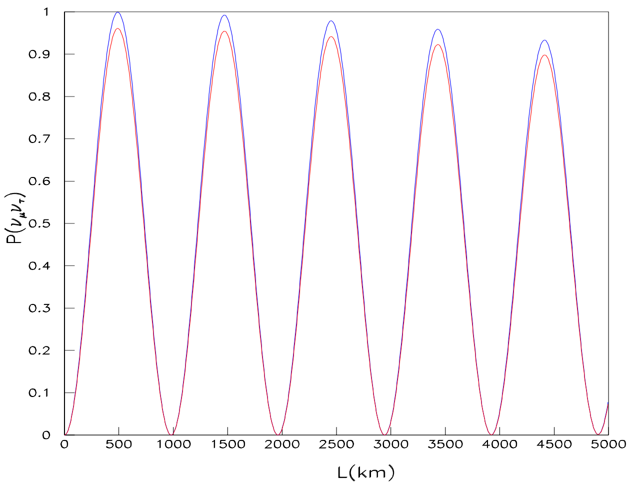
3ν mixing $\leftrightarrow$ link between atmospheric and solar oscillations (θ_{13})

Measure oscillations $\nu_e \leftrightarrow \nu_\mu, \nu_\tau$ or $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$ with $L_{osc} \sim \frac{E_\nu}{\Delta m^2_{atmos}}$

$\theta_{13} = 0$	$\theta_{13} \neq 0$
$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = c^2_{23}\ \sin^2 2\theta_{12}\ \sin^2\left(\frac{\Delta_{12}L}{2}\right)$	$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = \begin{aligned} & c^2_{23}\ \sin^2 2\theta_{12}\ \sin^2\left(\frac{\Delta_{12}\,L}{2}\right) \\ & + s^2_{23}\ \sin^2 2\theta_{13}\ \sin^2\left(\frac{\Delta_{23}\,L}{2}\right) \\ & + \tilde{J}\cos\left(\pm\delta - \frac{\Delta_{23}\,L}{2}\right)\ \frac{\Delta_{12}\,L}{2}\sin\left(\frac{\Delta_{23}\,L}{2}\right) \end{aligned}$

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



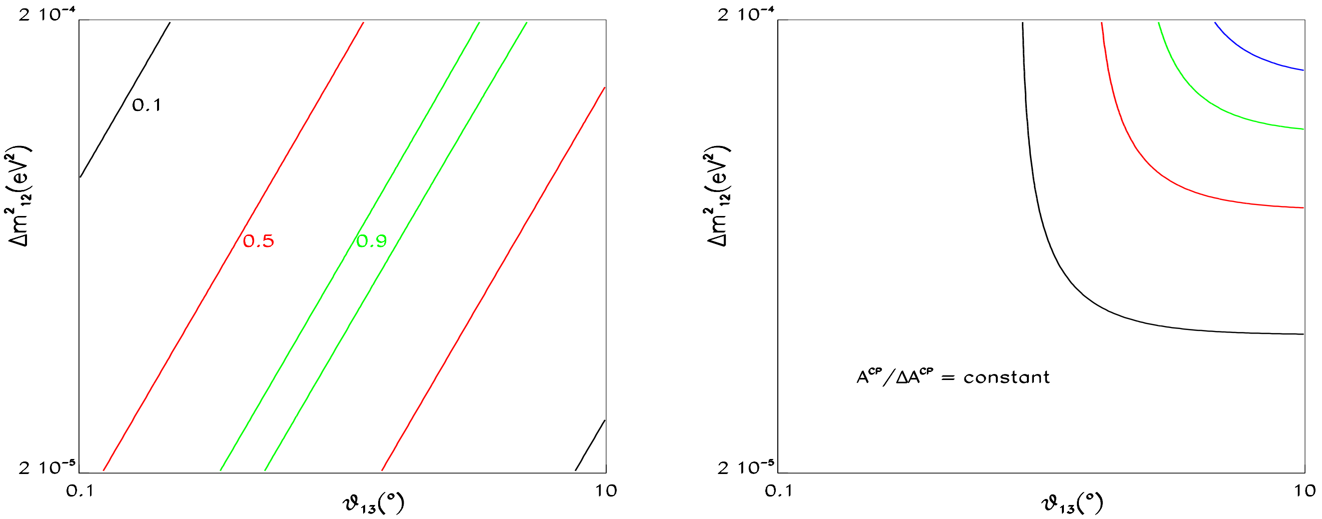


Leptonic CP violation ↔ **disentangle** (θ_{13},δ) **and** $\delta\neq 0$

Observability of CP-violation ↔ measurable CP-asymmetries:

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

Asymmetries can be quite large for subleading transitions $\nu_e\to\nu_\mu,\nu_\tau$:



$\mathcal{O}(1)$ when the atmospheric and solar oscillation terms are of similar size

But disentangling (θ_{13}, δ) is not so easy due to correlations and degeneracies!

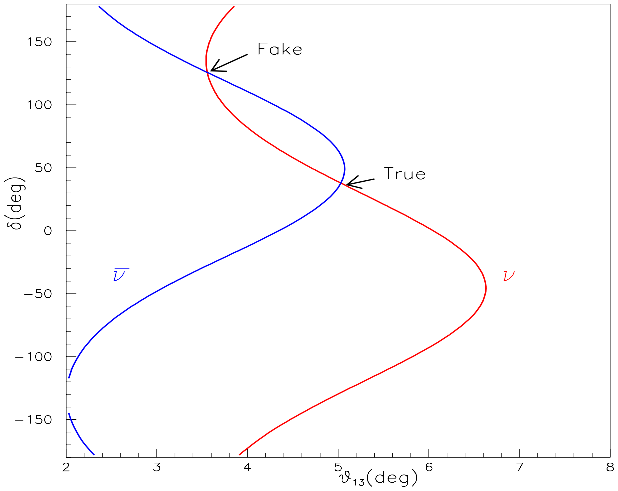
Burguet-Castell, Gavela, Gómez-Cadenas, P.H., Mena, hep-ph/0103258

At fixed E_ν, L there are generically two solutions for (θ_{13}, δ):

$$\left.\begin{aligned} P_{\nu_e \nu_\mu}(E_\nu/L, \theta_{13}, \delta) &= \text{Meas}_1 \\ P_{\bar{\nu}_e \bar{\nu}_\mu}(E_\nu/L, \theta_{13}, \delta) &= \text{Meas}_2 \end{aligned}\right\}$$

$\theta_{13}^{true}, \delta^{true}$

$\theta_{13}^{fake}(E_\nu/L), \delta^{fake}(E_\nu/L)$



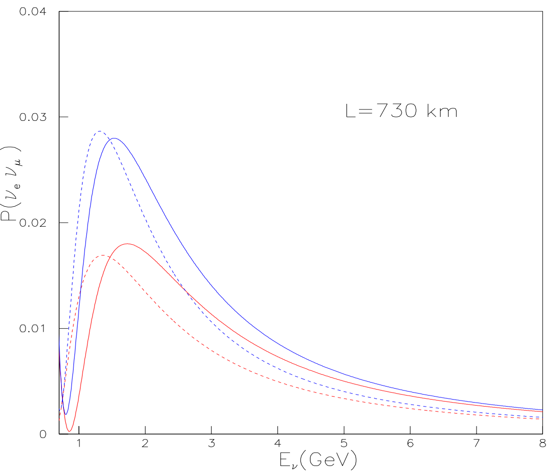
- Same problem for E_ν integrated signals, but the dependence of the fake solution is no longer E_ν/L

- Correlations with the other oscillation parameters: sign(Δm^2_{23}), sign$(\cos\theta_{23})$

Minakata, Nunokawa hep-ph/0108085; Barger, Marfatia, Whisnant, hep-ph/0112119

Resolving degeneracies

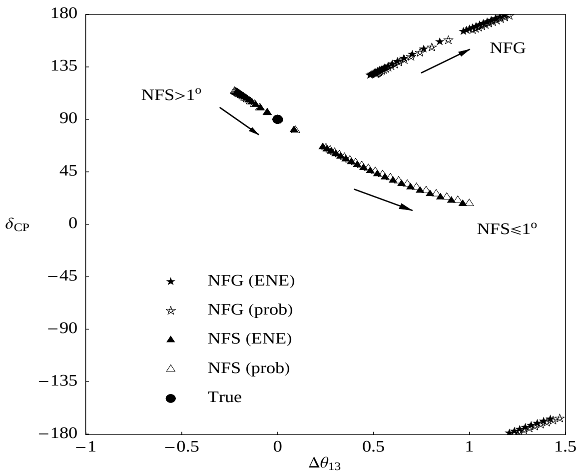
- Have spectral information on oscillation signals → ν energy resolution



$P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)}(E_\nu,\theta_{13},\delta)$ and
$P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)}(E_\nu,\theta_{13}^{\rm fake}(\langle E_\nu\rangle),\delta^{\rm fake}(\langle E_\nu\rangle))$
are equal at $E_\nu=\langle E_\nu\rangle$ but differ elsewhere

- Combine experiments differing: $\langle E_\nu\rangle/L$, neutrino fluxes or matter effects

- Include measurements of other flavor channels: silver channel $\nu_e\to\nu_\tau$



Donini, Meloni, Miggliozzi, hep-ph/0206034
Donini, Meloni, Rigolin, hep-ph/hep-ph/0312072

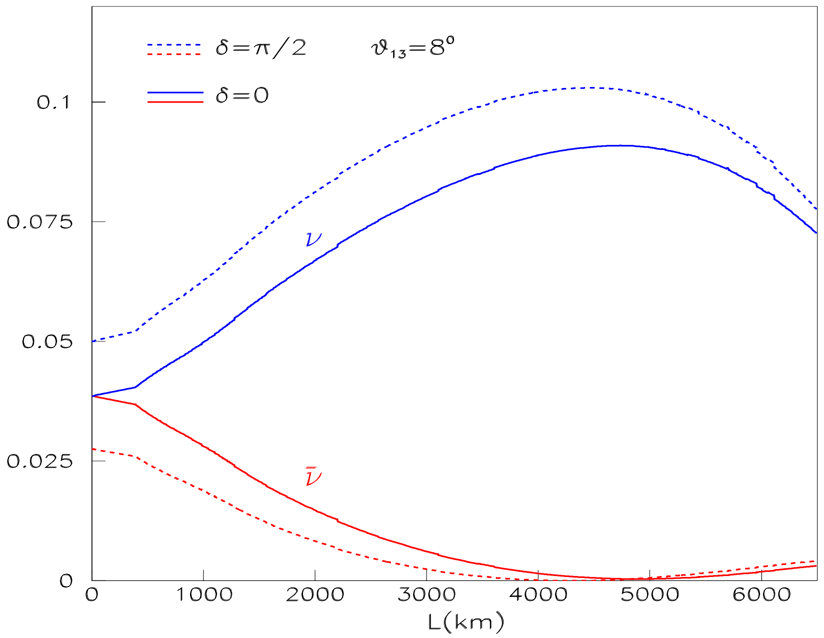
Determine the neutrino spectrum

The same measurements are sensitive to sign(Δm^2_{13}) , because neutrino propagation in the Earth gets modified by coherent forward scattering on electrons:

Wolfenstein, Mikheyev,Smirnov

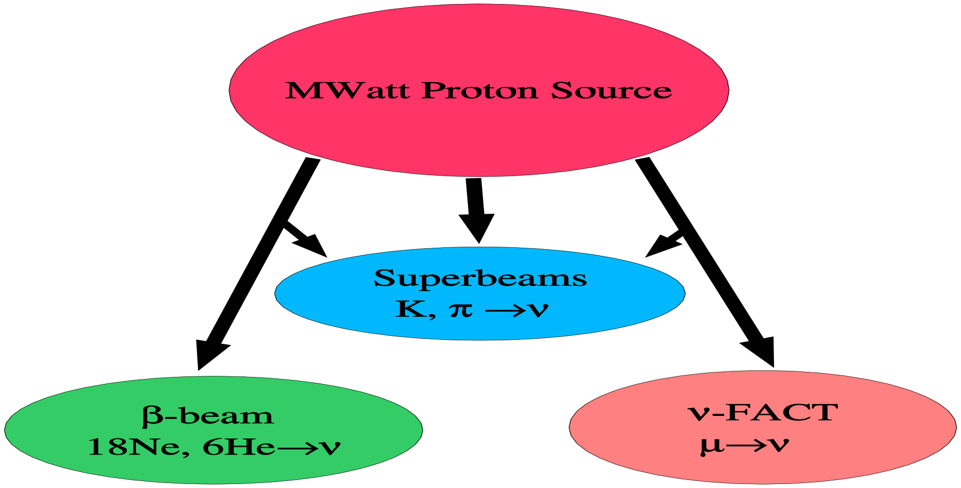
$$|\Delta m^2_{13}| \quad \Rightarrow |\Delta m^2_{13} \pm 2\sqrt{2} G_F N_e E_\nu| \qquad \sin^2 2\theta_{13} \quad \Rightarrow \sin^2 2\theta_{13} \left(\frac{\Delta m^2_{13}}{\Delta m^2_{13} \pm 2\sqrt{2} G_F N_e E_\nu} \right)^2$$

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})



The experimental challenge

We need to measure for the first time small oscillation probabilities at $E_\nu/L \sim \Delta m^2_{atmos}$: need more intense and purer ν sources



MWatt Proton Source

Superbeams
K, π ⟶ν

β-beam
18Ne, 6He⟶ν

ν-FACT
μ⟶ν

Zuchelli

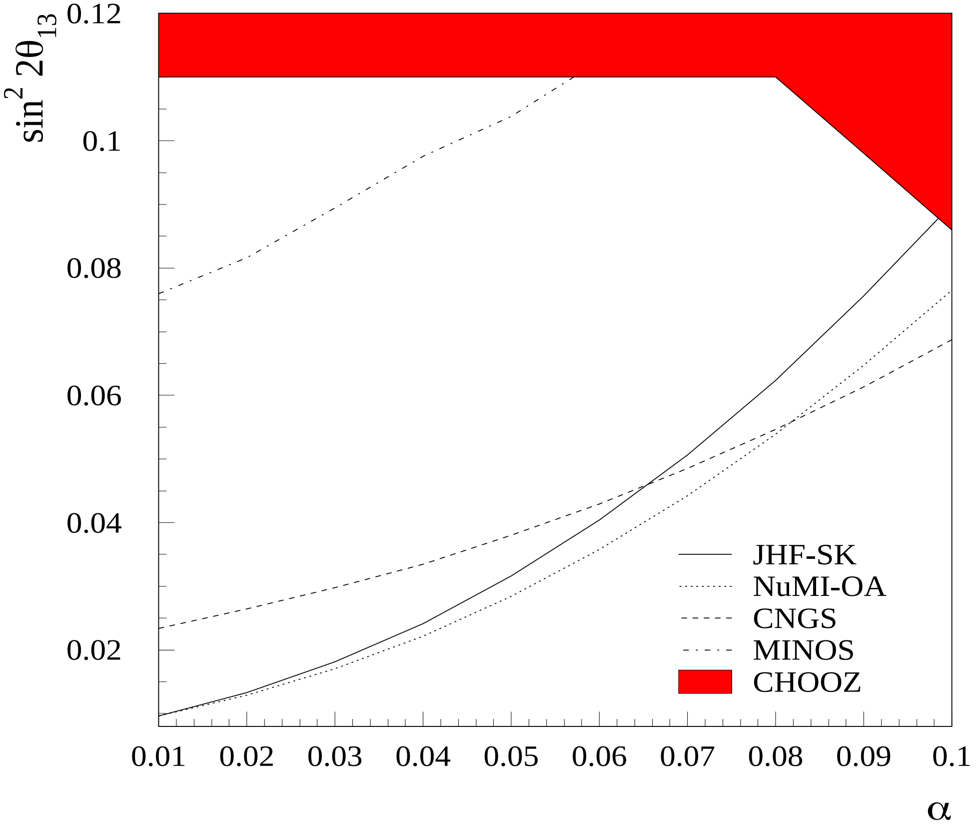
Superbeams:

$$\begin{aligned} \pi, K \rightarrow \quad & \nu_\mu \quad O(1\%)\, \nu_e\ \bar{\nu}_\mu; \\ & \nu_\mu \quad \rightarrow \nu_e \rightarrow e^- \end{aligned}$$

J-PARC, NUMI-OA

$$\nu_e \rightarrow \nu_e \rightarrow e^-$$

$\theta_{13} = 4^{\circ} \rightarrow$



P. Migliozzi, hep-ph/0311269

$\alpha \equiv \frac{\Delta m^2_{12}}{\Delta m^2_{23}} \sim 0.03$ for best fit values

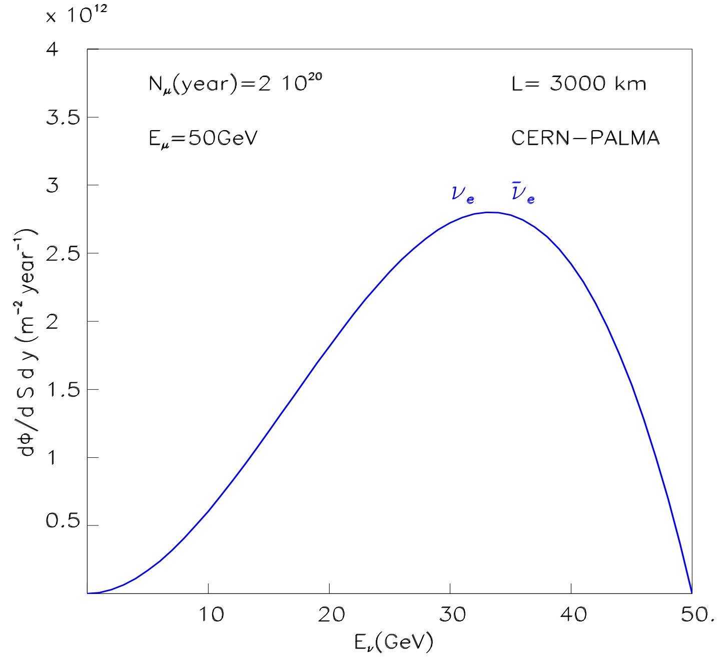
- **Neutrino factory** ν from muon decay

$$\mu^- \to e^- \quad \nu_\mu \quad \bar{\nu}_e$$

$$\bar{\nu}_e \to \bar{\nu}_\mu \to \mu^+$$

$$\nu_\mu \to \nu_\mu \to \mu^-$$

$$\left.\frac{d\Phi^{\mathrm{lab}}}{dSdy}\right|_{\theta\simeq 0} \simeq \frac{N_\mu}{\pi L^2} 12\gamma^2 y^2(1-y) \qquad y=\frac{E_\nu}{E_\mu}$$



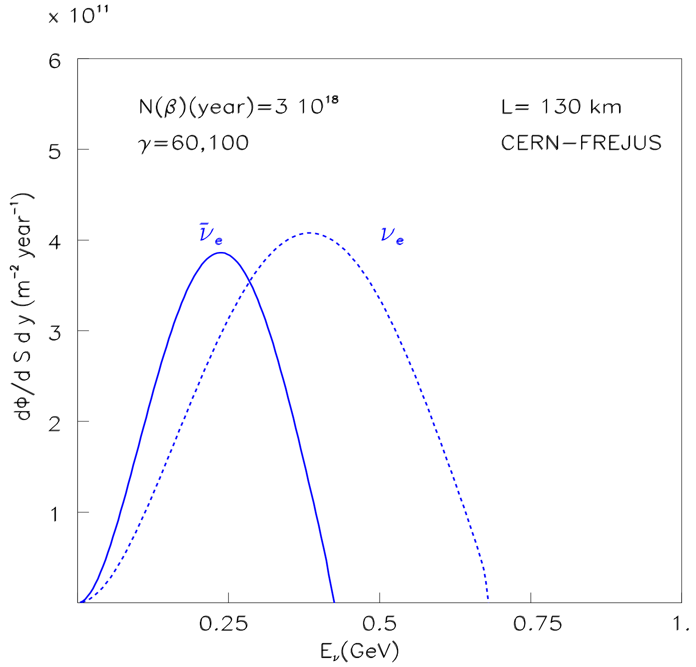
- ***β*-beams** from boosted heavy ions decays

$$^6He^{++} \to ^6_3 Li^{+++} \, e^- \quad \bar{\nu}_e$$

$$\bar{\nu}_e \to \bar{\nu}_\mu \to \mu^+$$

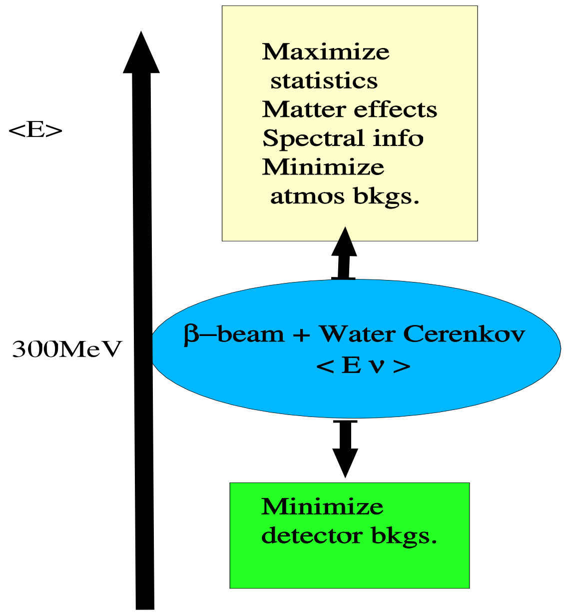
$$\left.\frac{d\Phi^{\mathrm{lab}}}{dSdy}\right|_{\theta\simeq 0} \simeq \frac{N_\beta}{\pi L^2} \frac{\gamma^2}{g(ye)} y^2(1-y)\sqrt{(1-y)^2 - y_e^2}$$

$$y=\frac{E_\nu}{2\gamma E_0},\, y_e = m_e/E_0$$



Optimization of $\langle E_\nu \rangle$, L (with $\langle E_\nu \rangle / L \sim \Delta m^2_{atmos}$)

Complex problem because of contradicting requirements: maximize intensity, minimize backgrounds, useful spectral information, measure the golden and silver channels, have sizeable matter effects,...



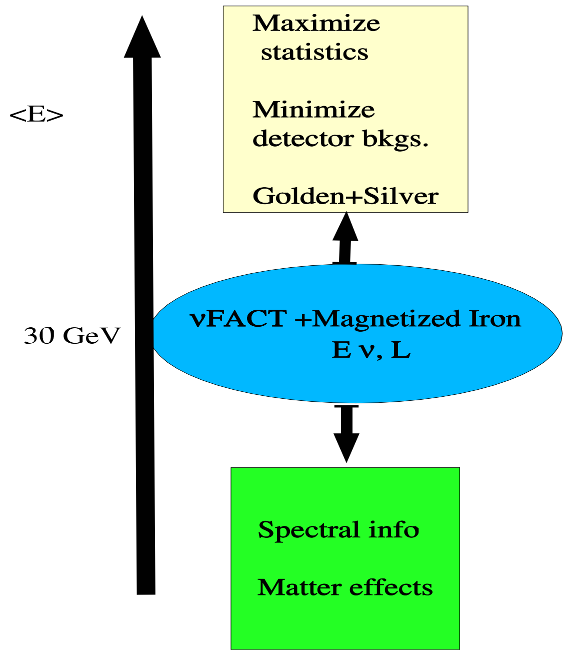
<E>

300MeV

Maximize
statistics
Matter effects
Spectral info
Minimize
atmos bkgs.

β–beam + Water Cerenkov
< E ν >

Minimize
detector bkgs.



<E>

30 GeV

Maximize
statistics

Minimize
detector bkgs.

Golden+Silver

νFACT +Magnetized Iron
E ν, L

Spectral info

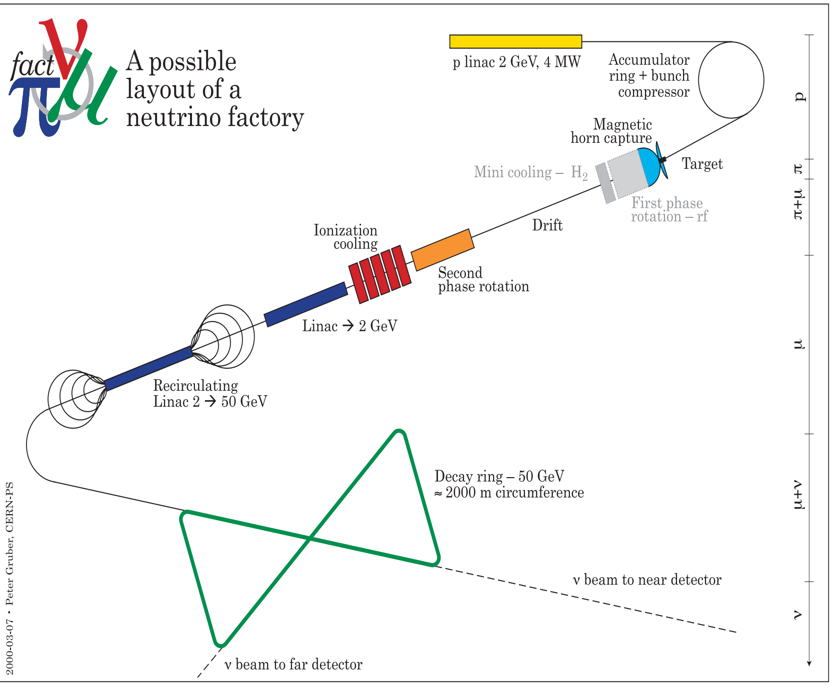
Matter effects

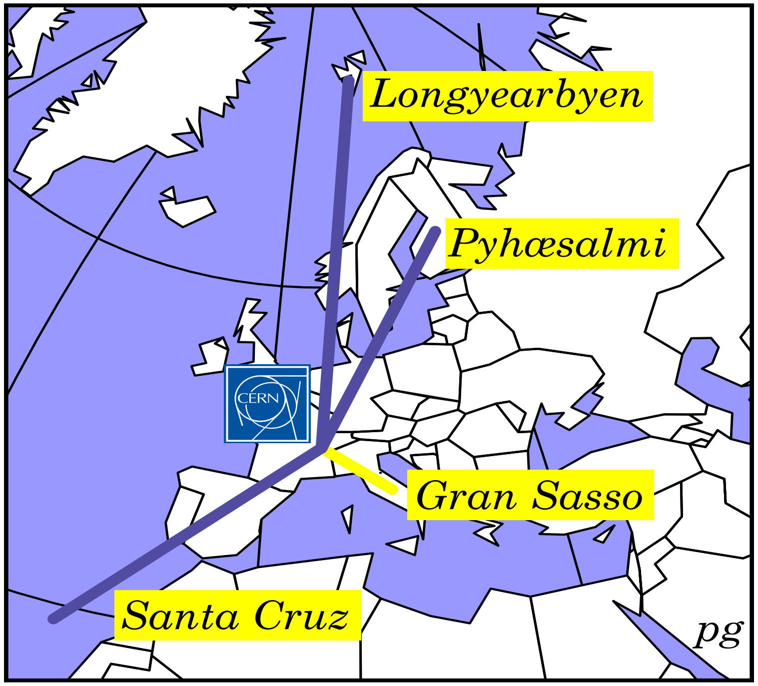
Constraint:

Feasibility: machine, baseline

Neutrino Factory

Standard setup: $L = 3000\text{km}$, $E_\mu = 50\text{GeV}$, 40Kton magnetized iron calorimeter



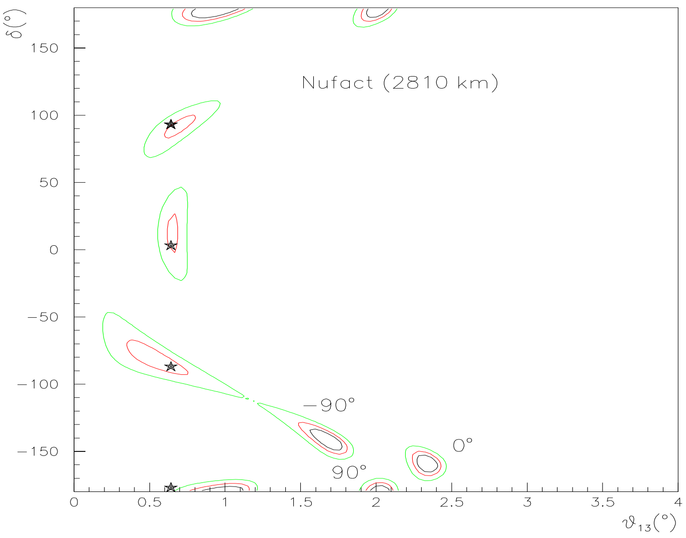


Great physics potential: sensitive to $\sin^2\theta_{13} \leq 10^{-4}$, sensitivity to $\text{sign}(\Delta m^2_{23})$ in a large part of parameter space, $\mathcal{O}(1\%)$ precision in atmospheric parameters!

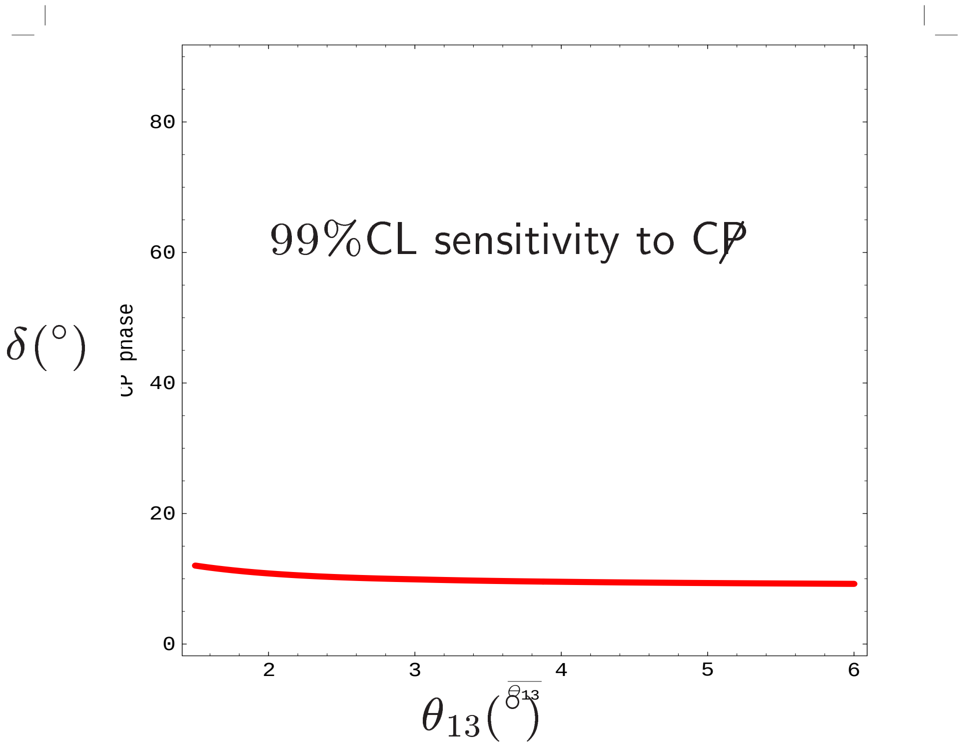
Sensitivity to CP violation compromised by degeneracies

Three extra handles:

1. Combination with a very long baseline
2. Combination with associated superbeam, SPL
3. Measure silver channel at $L = 730$km



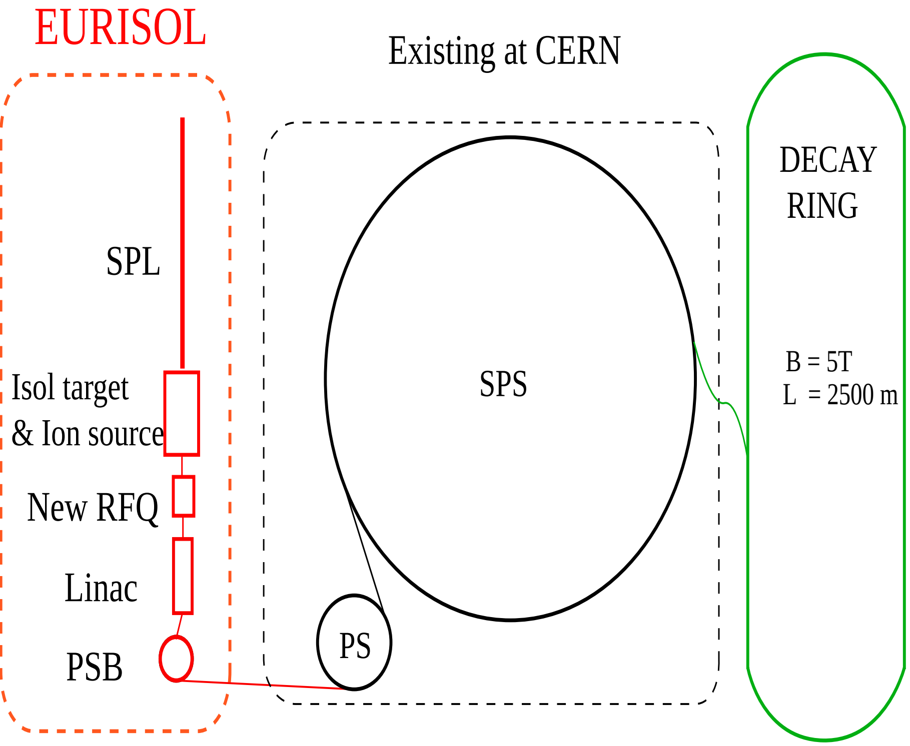
Golden(2810 km)+Silver (732 km)
+ SPL (130 km)



Mena

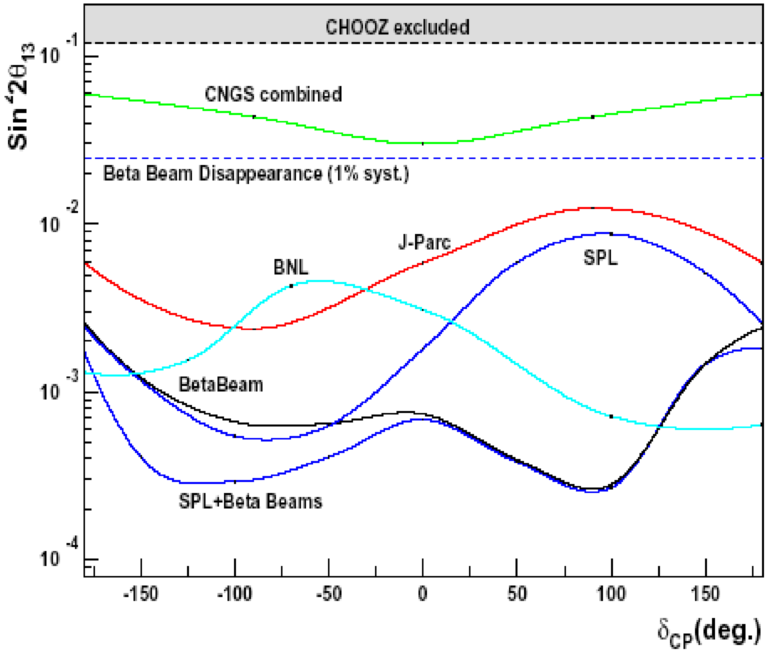
β-beam

The standard setup (talk by M. Lindroos): feasible today!



$2.9\ 10^{18}\ {}^{6}\text{He},\ \gamma({}^{6}\text{He}) = 65$

$1.1\ 10^{18}\text{Ne},\ \gamma({}^{18}\text{Ne}) = 100,$



↓ 130 km

Mton
Water Cerenkov

@ FREJUS

Bouchez, Lindroos, Mezzetto
hep-ex/0310059

Even though the fluxes are not so different there are four big limitations with respect to the Neutrino Factory:

	β-beam		Nufact	
Intensity	small $\sigma_{\nu,\bar\nu}$	$\downarrow$	large $\sigma_{\nu,\bar\nu}$	$\uparrow$
Systematics	$\delta\sigma_{\nu,\bar\nu}$ large	$\downarrow$	$\delta\sigma_{\nu,\bar\nu}$ small	$\uparrow$
Degeneracies correlations	E_ν resolution $\oplus$ SPL	$\downarrow$ $\sim$	Silver channel $\oplus$ SPL	$\uparrow$ $\uparrow$
ν spectrum	no matter eff.	$\downarrow$	large matter eff.	$\uparrow$

Higher γ β-beam ?

Higher energies can be achieved with existing CERN accelerators: LHC !

In principle:

$$\gamma_{max}(^{6}He) = 2488.08$$

$$\gamma_{max}(^{18}Ne) = 4158.19$$

In practice: a feasability study is required

- Unavoidable loses when injecting in the LHC can be compensated by a different acceleration scheme (e.g. atmospheric background is much smaller and longer or more bunches are possible)
- Complexity of the decay ring increases
- Interference with LHC programme
- An alternative to LHC could be a refurbished SPS with superconducting magnets

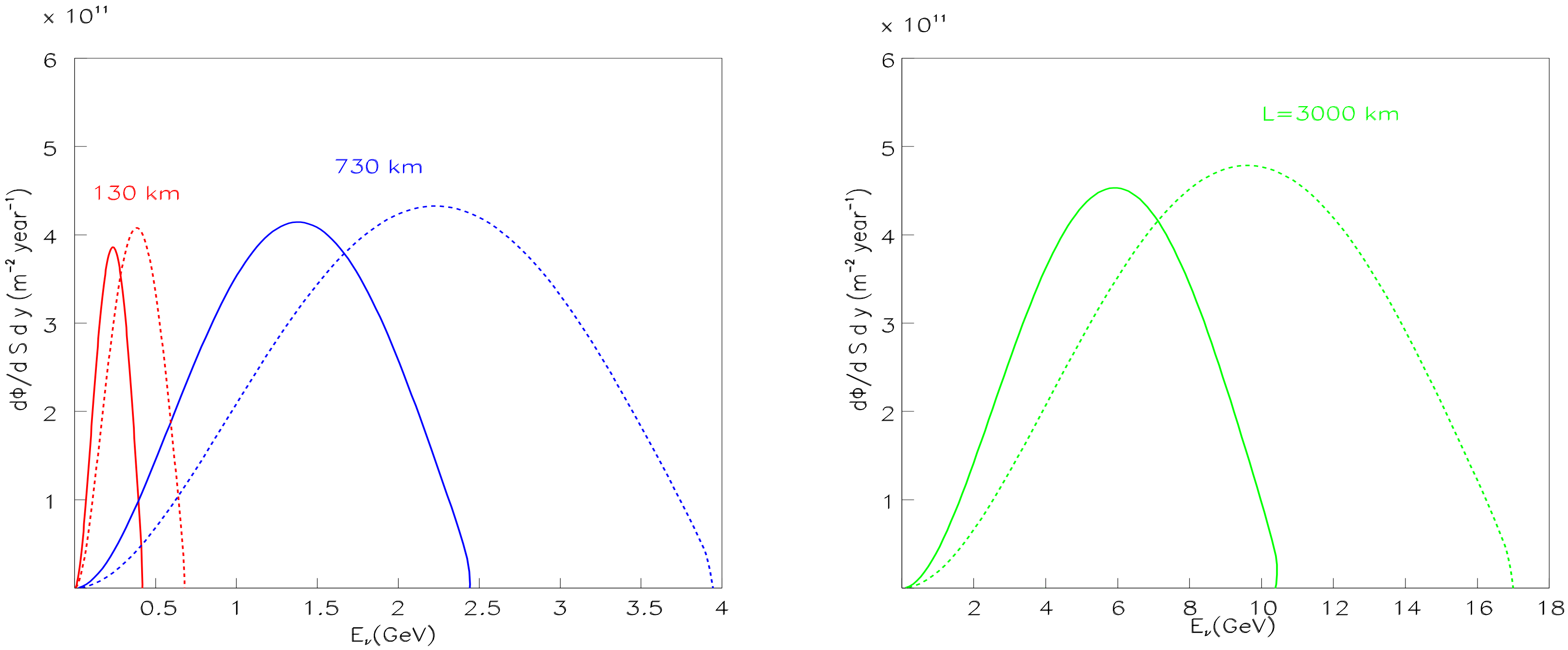
A β-beam will not happen tomorrow and there is time !!

Major improvement in the physics potential !

J.Burguet-Castell, D. Casper, J.J. Gómez-Cadenas, P.H., F.Sánchez, hep-ph/0312068

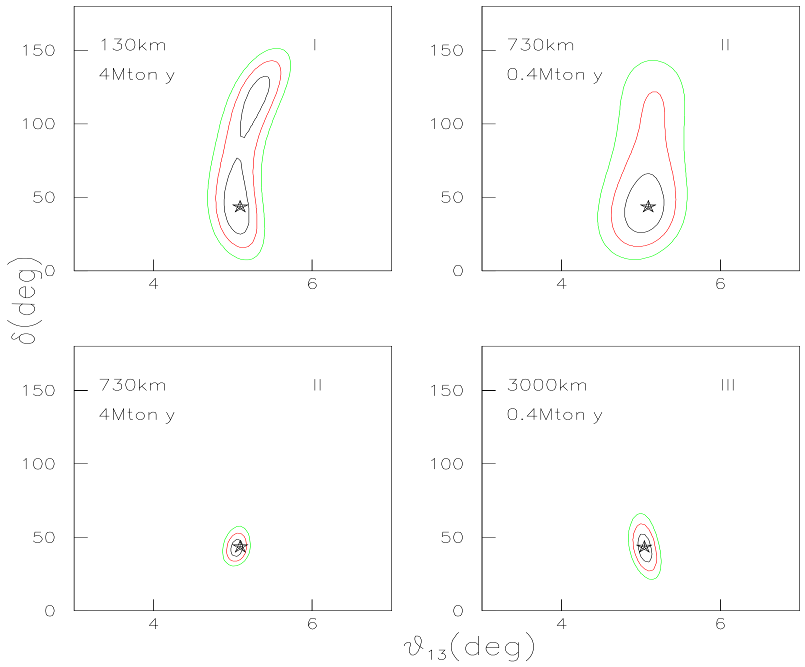
Comparison of three setups:

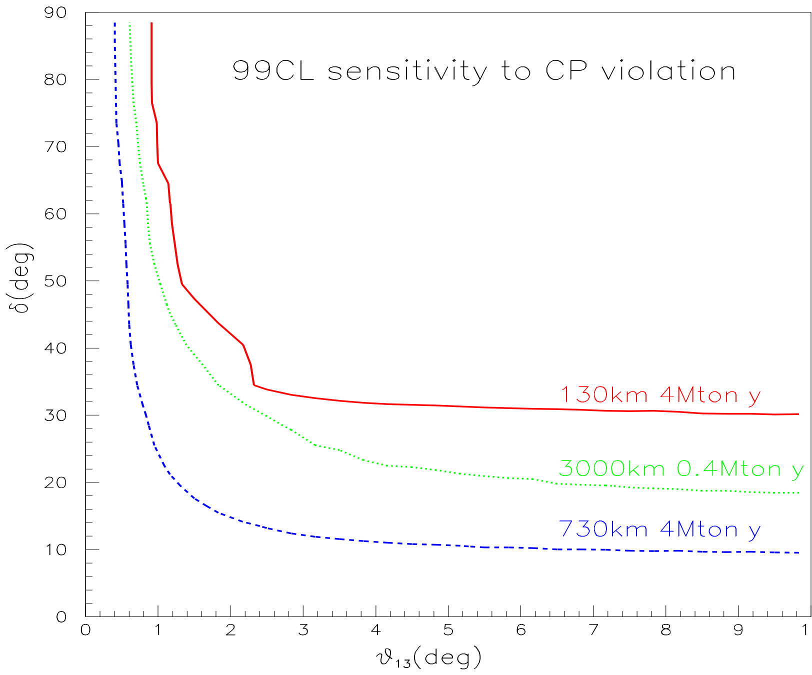
γ	$L(km)$	$\bar{\nu}_e$ CC (KTon y)	ν_e CC (KTon y)	$\langle E_\nu \rangle (GeV)$
60/100	130	4.7	32.8	0.23/0.37
350/580	730	57.5	224.7	1.35/2.18
1500/2500	3000	282.7	993.1	5.80/9.39



Sensitivity to θ_{13}, δ

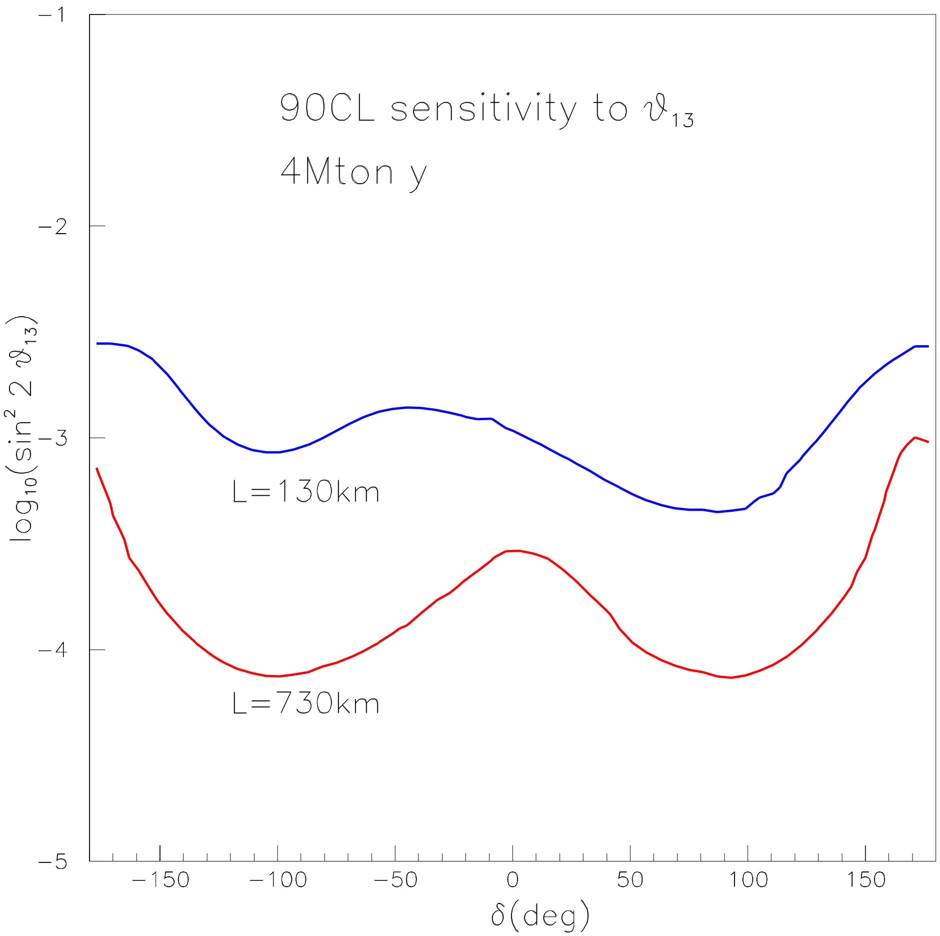
Setups I, II: 400 Kton water Cerenkov, Setup III: 40 Kton tracking calorimeter





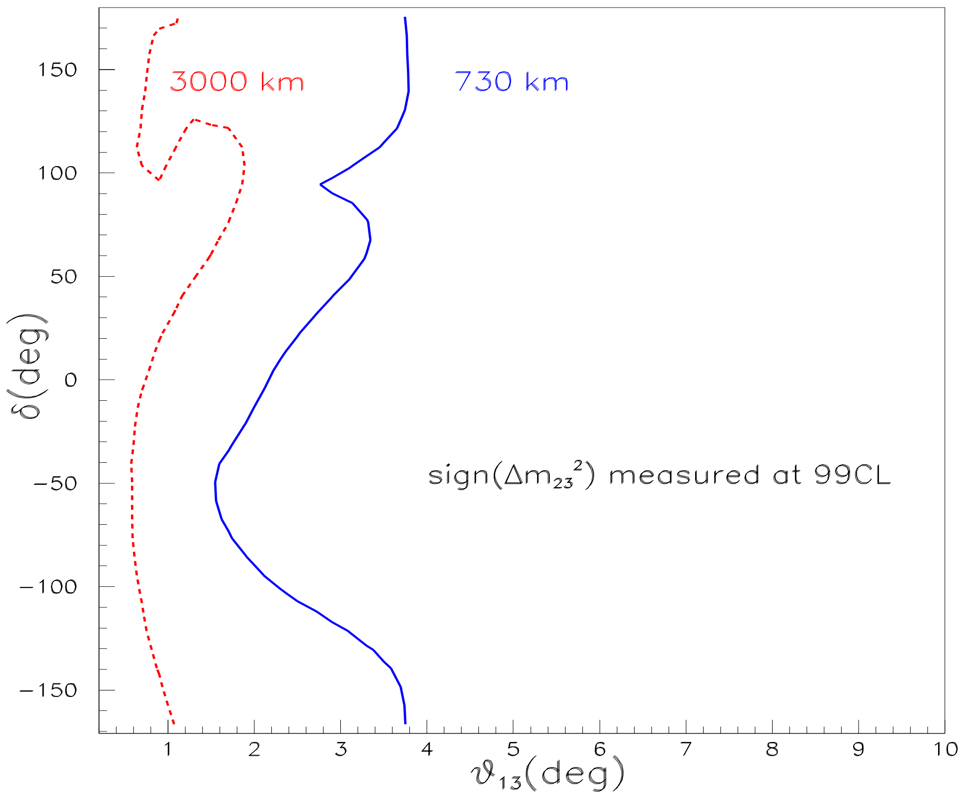
- Higher intensity
- Energy resolution reduces correlations and degeneracies

Sensitivity to $\theta_{13} \neq 0$



Sensitivity to the sign(Δm^2_{23})

In Setup I, matter effects are negligible, they are sizeable in Setup II and quite large in Setup III



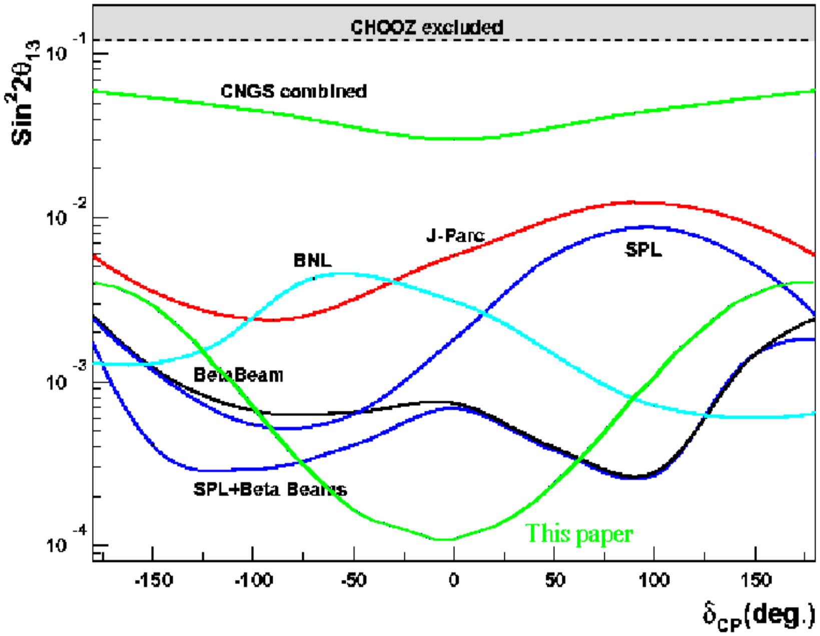
The neutrino mass spectrum can be measured in a large region of parameter space

Highest γ β-beam ($\gamma > 1500$) $\oplus$ instrumented surface detector (15 m× 15 m) at 730km (CERN-Gran Sasso) *Terranova, Marota, Migliozzi, Spinetti, hep-ph/0405081*

- $\langle E_\nu \rangle / L > \Delta m^2_{atmos}$ (off-peak): Signal $\sim \sigma \times \Phi \times P_{\nu_e \nu_\mu} \sim \mathcal{O}(E_\nu)$

- Massive detector for μ from the rock: Eff. mass $\sim \mu$ range $\sim E_\mu$

Sensitivity to δ and matter effects are compromised by the off-peak configuration, but impressive sensitivity to θ_{13}



Conclusions

- The flavour lepton sector of the SM that we are starting to reveal might give us some clues at to what lies beyond

- ν with their tiny masses are no longer good candidates for dark matter but they are to visible matter: they could explain the matter/antimatter asymmetry in the Universe

- A lot has been learned in recent years thanks to an ingenious experimental effort

- New discoveries in this field are likely with more precise neutrino oscillation experiments

- There are several very promising possibilities: superbeams, Neutrino Factories, β-beams which might differ in their optimal baselines, energies (the most physics-ambitious roadmap is still to be clarified)...but they all require

The rising star of ν physics