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"Sensitivities comparison EU/US/Japan"

- Introduction
- Ingredients for a comparison
  - Signal Efficiency
  - Backgrounds
  - Systematic Errors
  - Degeneracies
- Updated comparison charts

What future experiments will have to measure

1. Leptonic CP violation
2. Mass Hierarchy
3. θ_{13}
4. $\pi/4 - \theta_{23}$ and the octant

- Plus new physics searches through non standard neutrino interactions (NSI) and/or the unitariety of the mixing matrix

The above order following the prescriptions of the CERN strategy group

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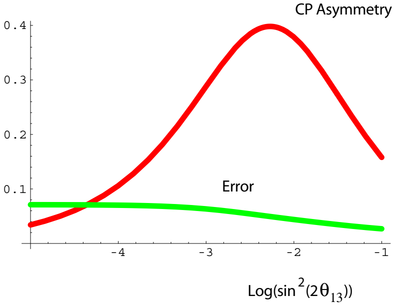
Neutrino mass model builders would probably order as 3,2,1,4

Measuring Leptonic CP violation

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)}$$



LCPV asymmetry at the first oscillation maximum, $\delta = 1$, Error curve: dependence of the statistical+systematic (2%) computed for a beta beam the fixed energy $E_\nu = 0.4$ GeV, $L = 130$ km.

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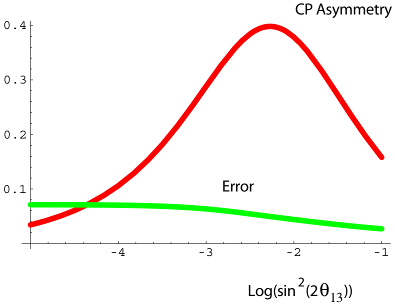

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- **The detection of such asymmetry is an evidence of Leptonic CP violation only in absence of competitive processes (i.e. matter effects, see following slides) ⇒ "short" Long Baseline experiments**

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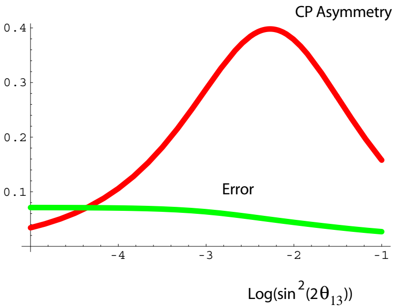

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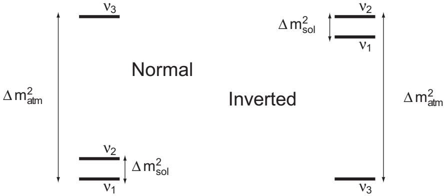
- **The detection of such asymmetry is an evidence of Leptonic CP violation only in absence of competitive processes (i.e. matter effects, see following slides) $\Rightarrow$ "short" Long Baseline experiments**
- Statistics and systematics play different roles at different values of θ_{13} $\Rightarrow$ impossible to optimize the experiment without a prior knowledge of θ_{13}
- Contrary to the common belief, the highest values of θ_{13} are not the easiest condition for LCPV discovery

An internal degree of freedom of neutrino masses is the sign of Δm^2_{31}: $\mathrm{sign}(\Delta m^2_{13})$.



This parameter decides how mass eigenstates are coupled to flavor eigenstates with important consequencies to direct neutrino mass and double beta decay experiments.

Neutrino Oscillations in Matter

$$P_{\theta_{13}} = \sin^2(2\theta_{13})\sin\theta_{23}{}^2 \sin^2((\hat{A}-1)\hat{\Delta})/(\hat{A}-1)^2;$$
$$p_{\sin\delta} = \alpha \sin(2\theta_{13})\zeta \sin\delta \sin(L\hat{\Delta}) \sin(\hat{A}\hat{\Delta}) \sin((1-\hat{A})\hat{\Delta})/((1-\hat{A})\hat{A});$$
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$\alpha = \mathrm{Abs}(\Delta m^2_{21}/\Delta m^2_{31})$; $\hat{\Delta} = \frac{L\Delta m^2_{31}}{4E}$ $\zeta = \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$
$\boldsymbol{\hat{A} = \pm a/\Delta m^2_{31}}$; $a = 7.6 \cdot 10^{-5}\rho \cdot E_\nu(GeV)$ $\rho = \text{matter density (g cm}^{-3})$
The $\hat{A}$ term changes sign with $\mathrm{sign}(\Delta m^2_{13})$

Matter effects require long “long baselines"

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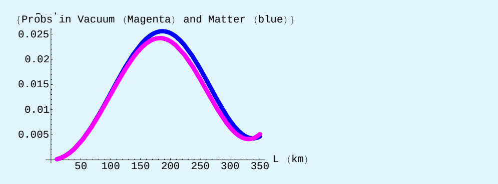
Matter effects require long "long baselines"

$\boldsymbol{E_\nu = 0.35\mathrm{GeV}\ L \simeq 130}$ **km**



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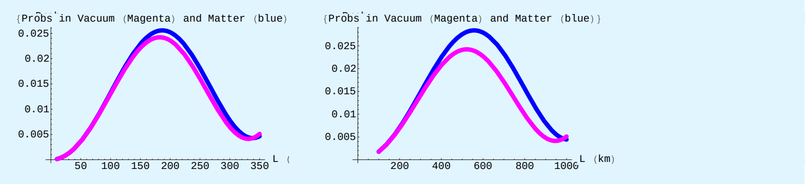
Matter effects require long "long baselines"

$\boldsymbol{E_\nu = 0.35\mathrm{GeV}}$ **$L \simeq$ 130 km** $\boldsymbol{E_\nu = 1\mathrm{GeV}}$ **$L \simeq$ 500 km**



Neutrino Oscillations in Matter

$$
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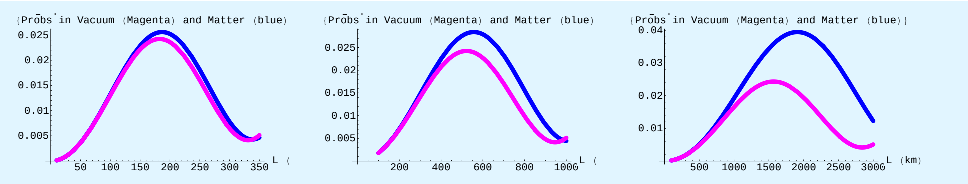
Matter effects require long "long baselines"

$E_\nu = 0.35\mathrm{GeV}$ $L \simeq 130$ km $\quad E_\nu = 1\mathrm{GeV}$ $L \simeq 500$ km $\quad E_\nu = 3\mathrm{GeV}$ $L \simeq 1500$ km



What to compare

Sensitivity: The highest value of a parameter (say θ_{13}) that can be excluded at a given CL in absense of a signal.
True value $= 0$; fit value $\neq 0$.

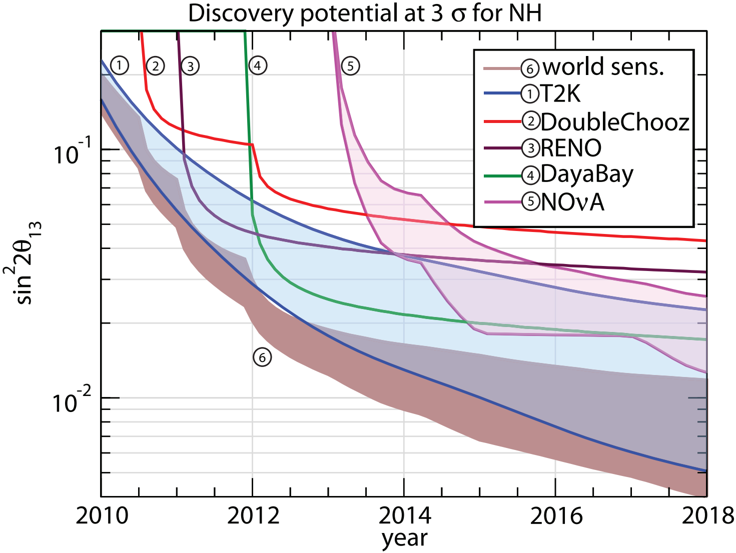
Discovery potential: The smallest value of a parameter that can be provide a signal that can't be fitted with a null value at a given CL.
True value $\neq 0$; fit value $= 0$.

Precision: Fractional value of one std over the parameter (i.e. $\frac{\sigma(\theta_{13})}{\theta_{13}}(\theta_{13})$)

In the following we will talk about sensitivity

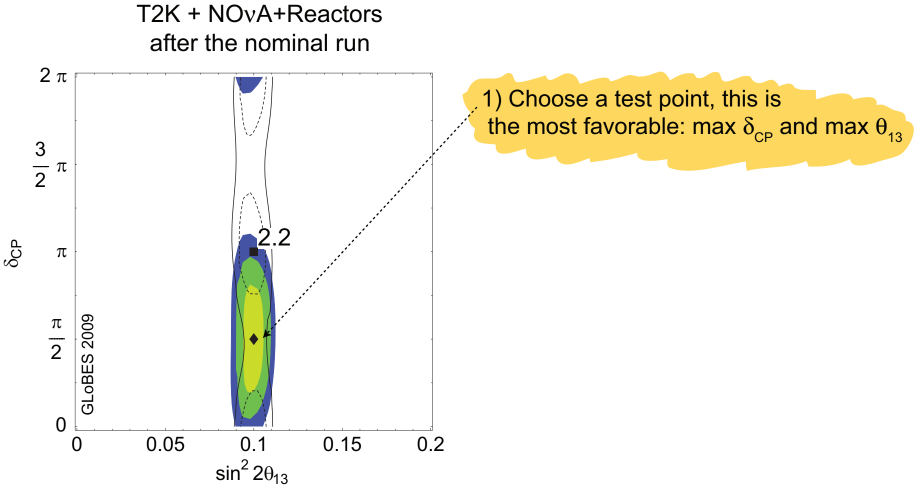
Status after this generation of LBL experiments: θ_{13}

From M.M. and T. Schwetz, arXiv:1003.5800



Status after this generation of LBL experiments: CPV

From P. Huber et al., JHEP 0911:044,2009.



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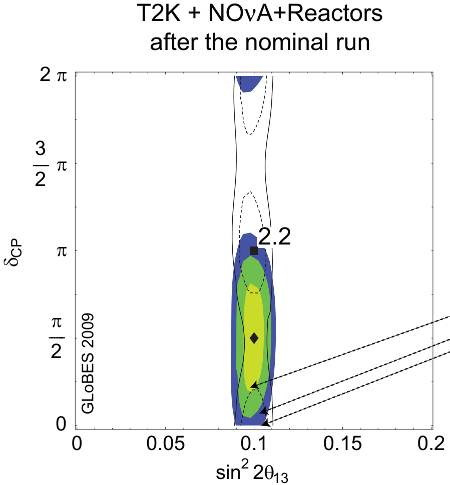

1) Choose a test point, this is the most favorable: max δ_{CP} and max θ_{13}

2) Fit to the expected sensitivity of the experiments: 1σ, 2σ, 3σ

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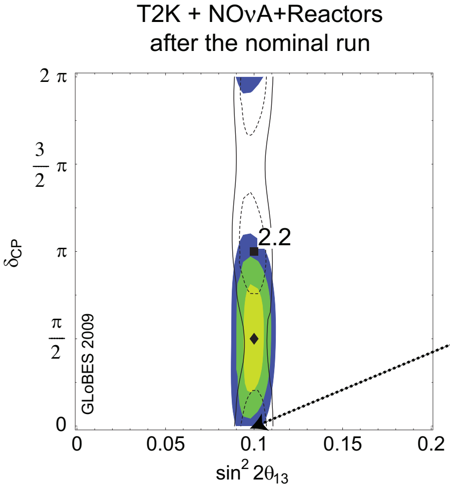


1) Choose a test point, this is the most favorable: max δ_{CP} and max θ_{13}

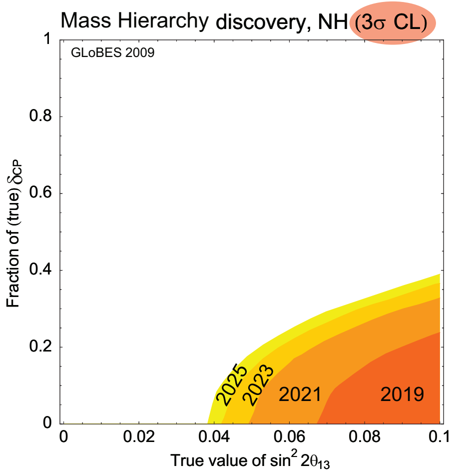
2) Fit to the expected sensitivity of the experiments: 1σ, 2σ, 3σ

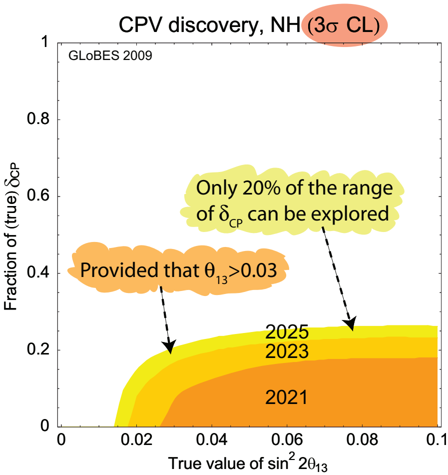
3) Null CP is compatible with data already at 2σ

Status after accelerator upgrades

From P. Huber et al., JHEP 0911:044,2009.

Prediction of sensitivity including a **fully optimized global run** (antineutrinos in T2K and NOνA) and **full upgrade of the accelerators**: 1.6 MW at J-PARC and 2.4 MW at FNAL (Project-X)





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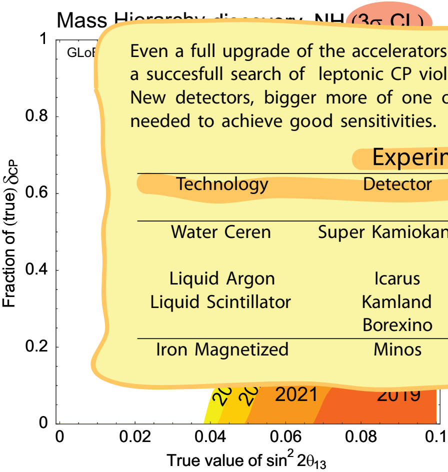
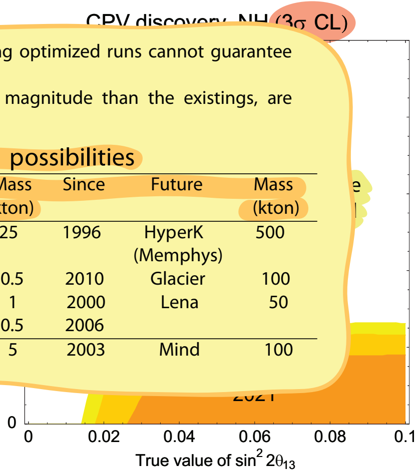


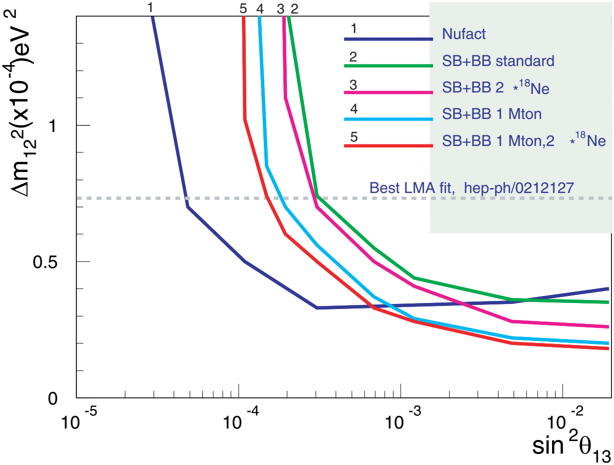


Even a full upgrade of the accelerators and long optimized runs cannot guarantee a succesfull search of leptonic CP violation.
New detectors, bigger more of one order of magnitude than the existings, are needed to achieve good sensitivities.

Experimental possibilities

Technology	Detector	Mass (kton)	Since	Future	Mass (kton)
Water Ceren	Super Kamiokande	25	1996	HyperK (Memphys)	500
Liquid Argon	Icarus	0.5	2010	Glacier	100
Liquid Scintillator	Kamland	1	2000	Lena	50
	Borexino	0.5	2006		
Iron Magnetized	Minos	5	2003	Mind	100

Apollonio et al. hep-ph/0210192 (see also MM hep-ex/0302007)



Soon after SNO and Kamland gave us the good news: LMA is the right solution and $\sin^2 2\theta_{12}$ is bigger than $7 \cdot 10^{-5}$ eV^2

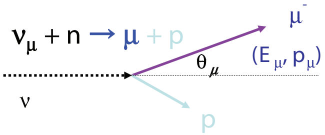
Before jumping to the comparisons

Things to take care about

- Energy reconstruction
- Background simulation
- Systematic errors
- Degeneracies

The quasi elastic case

Select single ring events and assume they are Quasi Elastic

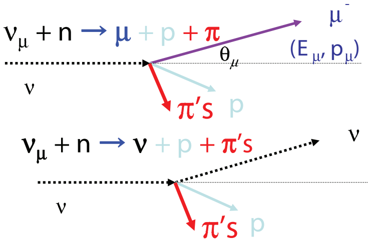


- **CC QE**
  - can reconstruct $E_\nu \leftarrow (\theta_\mu, p_\mu)$

$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2 / 2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

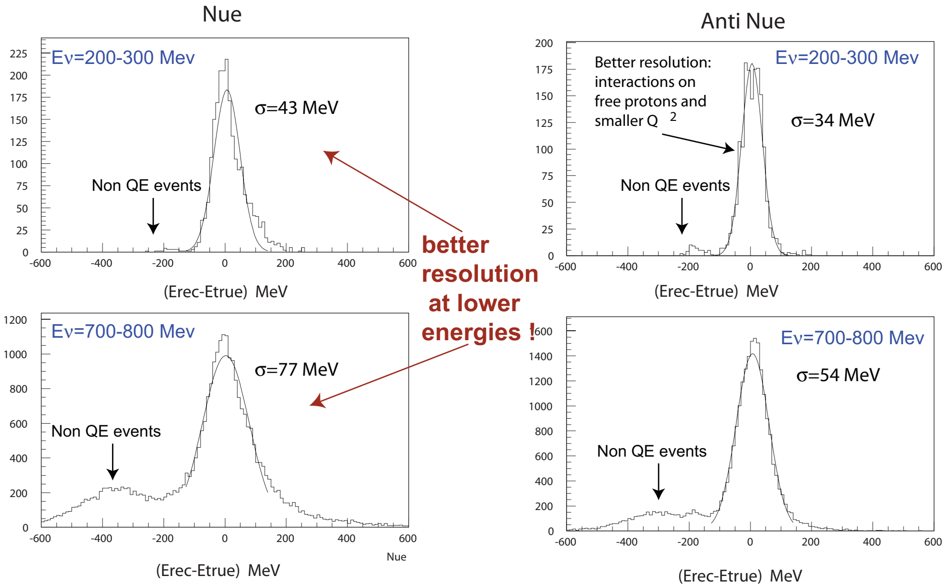
$\delta E \sim 60$ MeV $\quad \delta E/E \sim 10\%$

Single ring non Quasi Elastic are badly measured



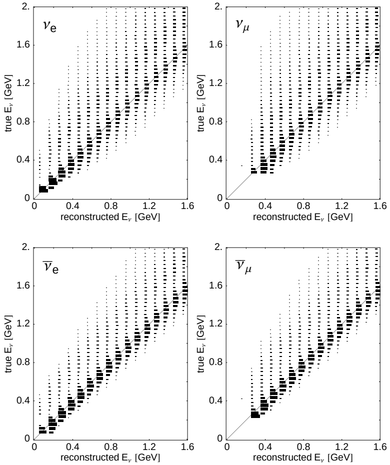
- bkg. for E_ν measurement
- High energy part
- bkg.for e-appearance

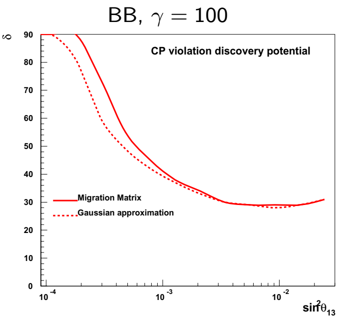
Goodness of energy reconstruction



Migration Matrixes

A gaussian assumption for energy resolution is a too crude approximation





N.B. DIS event reconstruction requires to precisely measure the hadronic shower → introducing again non-gaussianity of the energy resolution

Backgrounds

The ultimate limit for CPV and θ_{13} sensitivity are background rates and systematic errors.

In a Super Beam setup bacgkrounds come mainly from intrinsic ν_e that look like signal.

For Beta Beams and Nufacts where the intrinsic backgrounds are absent and the background rate small, it is mandatory to compute them as accurately as possibly, exploiting a full simulation and a full reconstruction.

Better if migration matrixes are built (most general case) but their energy spectrum is enough for a fair sensitivity computation. (Energy shape is important because it could be different from oscillated events, reducing the impact of the background rate, as in the case of beta beams).

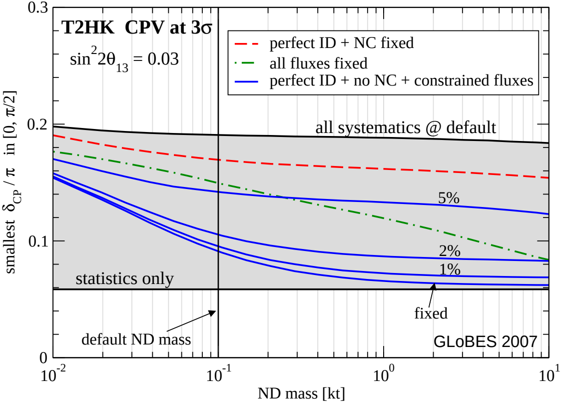
Quite often anyway background rates are just “guessed”: tipical case NC backgrounds assumed as a 10^{-4} fraction of CC interactions.

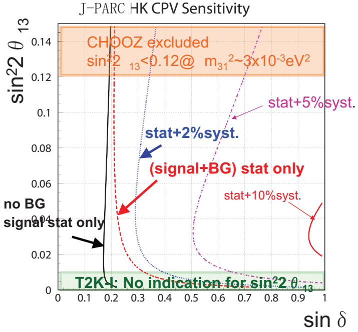
Systematic errors

They could completely destroy leptonic CP violation.

Default value are often 5% for SuperBeams, 2% for Neutrino Factory and 2-5% for Beta Beams.

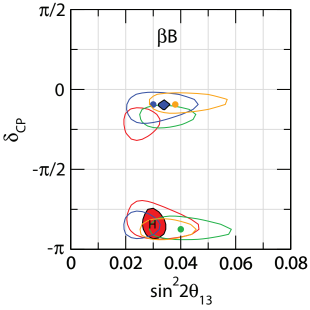
Are they realistic goals? From P. Huber, MM, T. Schwetz, JHEP **0803** (2008) 021 [arXiv:0711.2950 [hep-ph]].

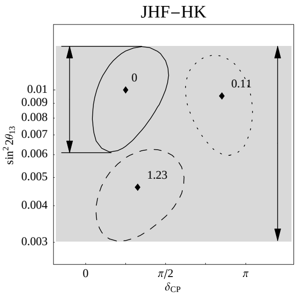


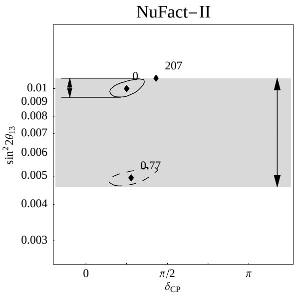


The problem is not that simple

- The 3 ν oscillation formula contains all the mixing matrix parameters and Δm^2. The parameters already measured do have errors that will influence the extraction of the unknown parameters.
- Several parameters still unknown: θ_{13}, δ_{CP}, sign(Δm^2) (hierarchy), the octant of θ_{23}. Different combinations of the above unknowns can fit the same data: $\Rightarrow$ **The eightfold degeneracy**



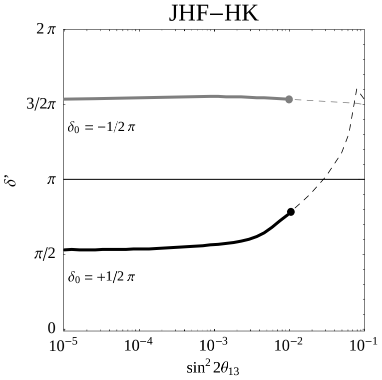




The π-transit problem

From Huber, Lindner, Winter, Nucl. Phys B645:3-48, 2002

The $\mathrm{sign}(\Delta m^2_{13})$ degenerate solution could show up at $\delta_{\mathrm{CP}} = \pi$ destroying any CPV sensitivity. Its position is function of θ_{13} and depends from the baseline.



Degeneracies (cont.)

To solve degeneracies:

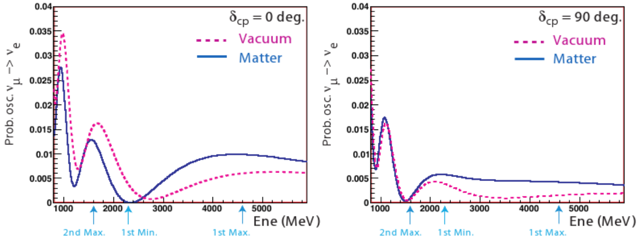
- A single experiment, single channel, can't get rid of degeneracies.
- The combination of different channels in the same detector can solve degeneracies, i.e. first a second oscillation maxima measurement in LBNE or at Okinoshima.
- Different signals in the same detector can also do the job, i.e. beta beams and atmospheric neutrinos.
- A third possibility is to combine the information of different detectors along the same neutrino beam, as exploited by several proposed neutrino factory configurations.
- Of course the combination of the above combinations can also measure all the unknown parameters: can we define an optimal strategy?

The second oscillation maximum

Studied for Dusel-LBNE, T2O (T2OK ?), PS2-Laguna

- The functional form of genuine CP and $\text{sign}(\Delta m^2_{13})$ terms (both bringing to $\nu \neq \overline{\nu}$) are different at the first and the second oscillation maxima.
- This gives a powerful handle to solve degeneracies.
- It is very challenging on the detector side, covering the 0.5-10 GeV energy range with good background rejection.
- Furthermore the longer distance brings to better sensitivities about mass hierarchy.
- The (high) price to pay is a factor 9 reduction on neutrino fluxes (the second maximum is three times more distant from the first), bringing to reduced sensitivities on θ_{13} and CPV.

From A. Rubbia, arXiv:1003.1921



The synergy with atmospheric neutrinos

P. Huber et al., Phys. Rev. D 71, 053006 (2005): Combining Long Baseline data with atmospheric neutrinos (that come for free in the megaton detector):

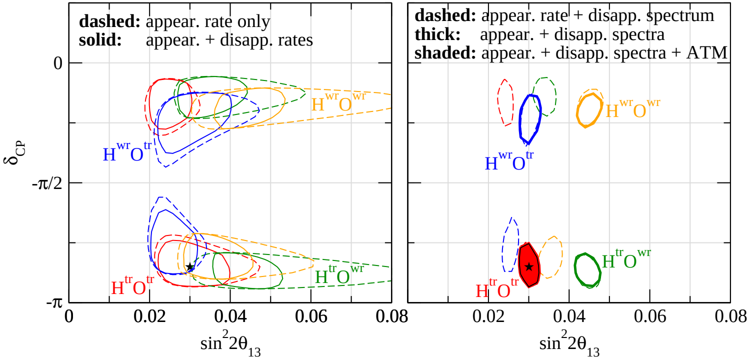
- Degeneracies can be canceled, allowing for better performances in θ_{13} and LCPV searches
- The neutrino mass hierarchy can be measured
- The θ_{23} octant can be determined.

The main reasons are:

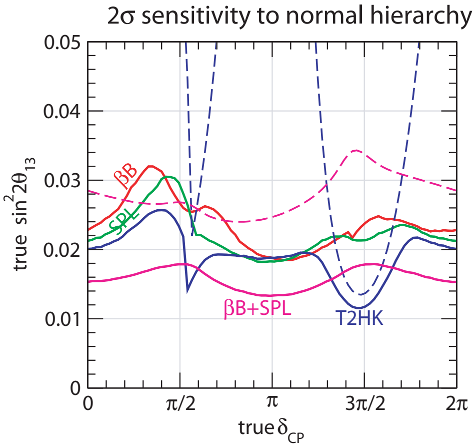
- **Octant** e-like events in the Sub-GeV data is $\propto \cos^2 \theta_{23}$
- **Sign** e-like events in the Multi-GeV data, thanks to matter effects, especially for zenith angles corresponding to neutrino trajectories crossing the mantle and core where a resonantly enhancement occurs.

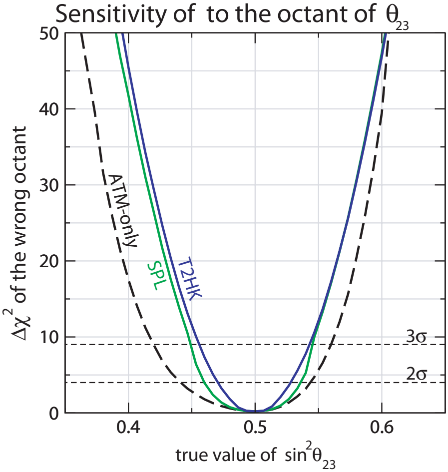
NOTE: LBL and atmospherics are a true synergy. They add to each other much more that a simple gain in statistics. Atmospherics alone could not measure the hierarchy, the octant, θ_{13} and LCPV. While the Beta Beam at short baselines could not measure the hierarchy as well as the octant.

J.E.Campagne, M.Maltoni, M.M., T.Schwetz, JHEP **0704** (2007) 003



Resolving degeneracies in SPL by successively using the appearance rate measurement, disappearance channel rate and spectrum, spectral information in the appearance channel, and atmospheric neutrinos. Allowed regions in $\sin^2 2\theta_{13}$ and $\delta_{\rm CP}$ are shown at 95% CL, and $\rm H^{tr/wr}(O^{tr/wr})$ refers to solutions with the true/wrong mass hierarchy (octant of θ_{23}). The true parameter values are $\delta_{\rm CP} = -0.85\pi$, $\sin^2 2\theta_{13} = 0.03$, $\sin^2\theta_{23} = 0.6$. The running time is $(2\nu + 8\bar{\nu})$ yrs.


2σ sensitivity to normal hierarchy
true sin²2θ13
true δCP
0
0.01
0.02
0.03
0.04
0.05
0
π/2
π
3π/2
2π
βB
SPL
βB+SPL
T2HK


Sensitivity of to the octant of θ23
Δχ² of the wrong octant
true value of sin²θ23
0
10
20
30
40
50
0.4
0.5
0.6
ATM-only
SPL
T2HK
3σ
2σ

Sensitivity Comparison

Based to arXiv:1005.3146, the EuroNu midterm physics report

WBB: Fermilab to Dusel, 1 MW for ν running, proton energy: 120 GeV, 2 MW for $\overline{\nu}$ running (5+5 yr), 100 kton liquid argon detector, according to Barger et al, Phys. Rev. D76:053005, 2007 (hep-ph/0703029). This setup is different from the proposed LBNE experiment.

T2KK: J-Parc ν beam running at 4 MW. 270 kton WC detector at Kamioka (295 km) and 270 kton WC detector in Korea (1050 km), Barger et al, Phys. Rev. D76:053005, 2007 (hep-ph/0703029).

PS2-Slanic CERN-PS2 SuperBeam fired to 100 kton LAr detector at Slanic, as computed by A. Rubbia, arXiv:1003.1921.

SPL: Neutrino beam from CERN-SPL running at 3.5 GeV, 4 MW. 440 kton WC detector at Frejus (130 km). Campagne et al. JHEP **0704** (2007) 003 (hep-ph/0603172).

Beta Beam $\gamma = 100$ Eurisol Beta Beam to Frejus (440 kton WC detector). Campagne et al. JHEP **0704** (2007) 003 (hep-ph/0603172).

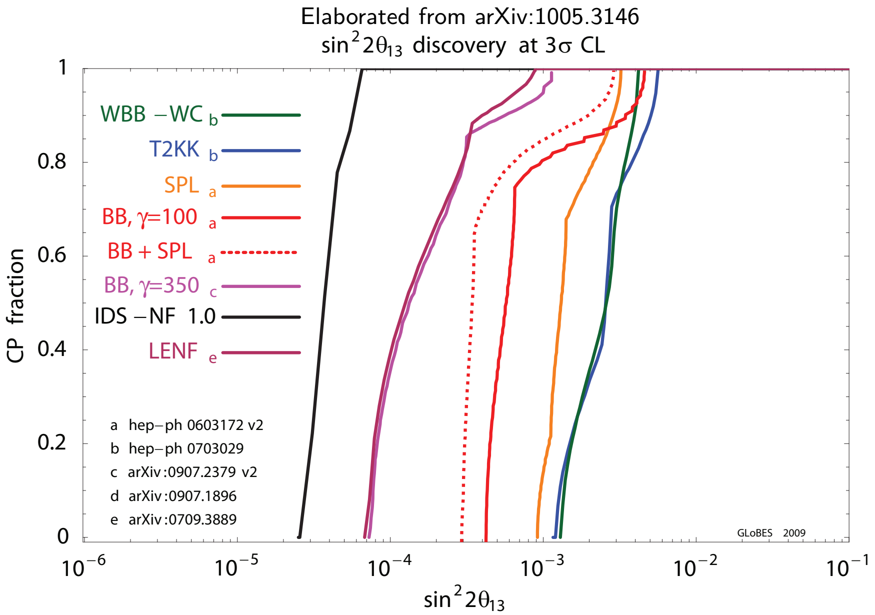
Beta Beam + SPL The combination of the above two.

Beta Beam $\gamma = 350$ Beta Beam at $\gamma = 350$, running $^{6}\mathrm{He}$ and $^{18}\mathrm{Ne}$ at the same decay rates as the Eurosol Beta Beam. WC detector of 500 kton at Canfranc (650 km). S. Choubey et al., JHEP 0912:020,2009 (arXiv:0907.2379)

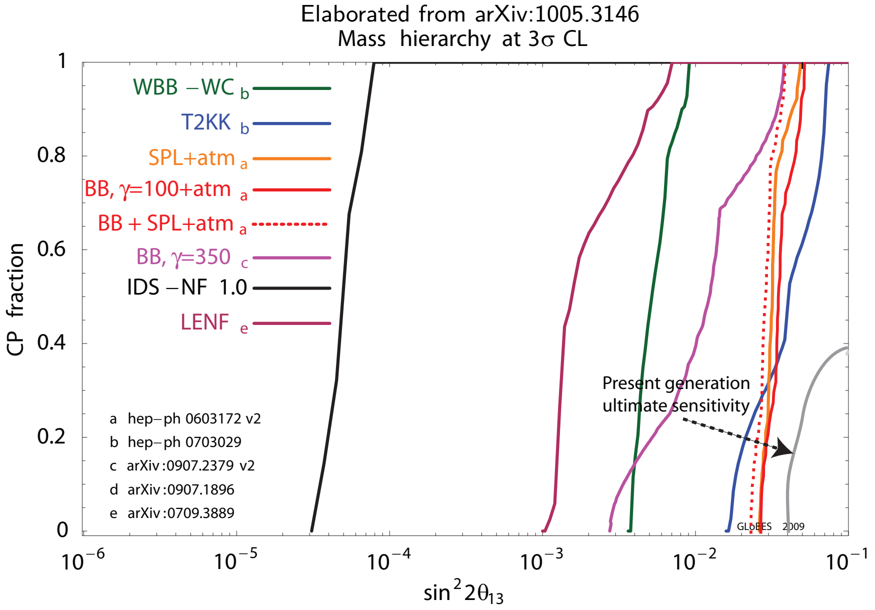
Low Energy Neutrino Factory (LENF) Neutrino Factory running at 4.12 GeV delivering 10^{21} muon decays/year for each sign, 30 kton Noνa like detector, fully magnetized (!) at 1480 km (Fermilab-Henderson mine). A. Bross et al, Phys.Rev.D77:093012,2008. (arXiv:0709.3889)

IDS 1.0 Neutrino Factory 25 GeV neutrino factory delivering $0.5 \cdot 10^{21}$ muon decays/year for each sign, a 50 kton iron magnetized detector and a 10 kton Emulsion Cloud Chamber, at 4000 km and a 50 kton iron magnetized detector at 7500 km.

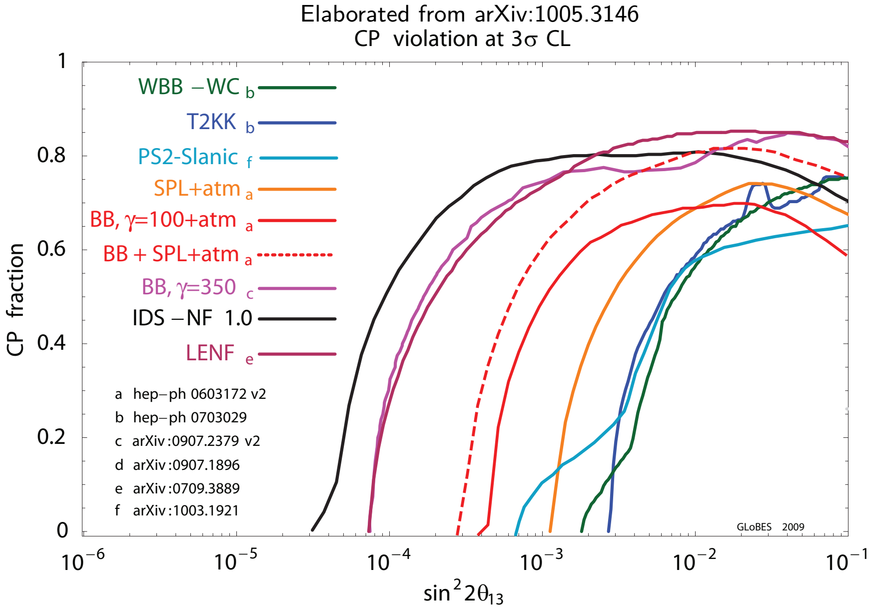
Sensitivity Comparison: θ_{13}



Sensitivity Comparison: $\mathrm{sign}(\Delta m^2_{13})$



Sensitivity Comparison: LCPV



Conclusions

In absence of any information about θ_{13} it is impossible to define an optimal strategy.

I'm personally skeptical about optimal strategies and I'm more in favor of realistic, pragmatic approaches. Keeping in mind that the goal for the future is to discover Leptonic CP Violation.

Difficult exercise to understand what is realistic at CERN.

If θ_{13} is not within the reach of T2K and the reactors we have to plan Beta Beams or Neutrino Factories. This doesn't exclude a first stage with a Super Beam.