Phenomenology of future LBL experiments

Lecture II

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The leptonic mixing matrix, now

G.L. Fogli *et al.*, hep-ph/0506083

- $|\Delta m^2_{atm}| = (2.4^{+0.5}_{-0.6}) \cdot 10^{-3}\ \mathrm{eV}^2$
- $\Delta m^2_{sol} = (8.0^{+0.8}_{-0.7}) \cdot 10^{-5}\ \mathrm{eV}^2$
- $\sin^2\theta_{23} = (0.34 - 0.63)$
- $\sin^2\theta_{12} = (0.20 - 0.34)$
- $\sin^2\theta_{13} \leq 0.035$

We do not know:

- The sign of $\Delta m^2_{atm} \to s_{atm}$
- Is it θ_{23} maximal?
- If not, is $\theta_{23} < 45^\circ$ or $\theta_{23} > 45^\circ \to s_{oct}$
- Is θ_{13} different from zero?

Neutrino sources

- Natural sources:
  - ★ The Sun $\longrightarrow \nu_e$
  - ★ Cosmic rays $\longrightarrow \nu_e, \nu_\mu$
  - ★ Supernovae and relic SNs $\longrightarrow \nu_e, \nu_\mu, \nu_\tau$
  - ★ Geoneutrinos $\longrightarrow \nu_e$

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  - ★ Supernovae and relic SNs $\longrightarrow \nu_e, \nu_\mu, \nu_\tau$
  - ★ Geoneutrinos $\longrightarrow \nu_e$
- Man-made sources:
  - △ Reactors: $n \to pe\ \bar{\nu}_e$
  - △ Conventional beams: $\pi^\pm \to \mu^\pm\ \nu_\mu(\bar{\nu}_\mu)$
  - △ Neutrino Factory: $\mu^\mp \to e^\mp\ \nu_\mu, \bar{\nu}_e(\bar{\nu}_\mu, \nu_e)$
  - △ Beta beam: ^{6} He $\to \bar{\nu}_e$, ^{18} Ne $\to \nu_e$

Foreseen bounds on θ_{13}

EXP	θ_{13}	$\sin^2(2\theta_{13})$	$\sin^2\theta_{13}$
Global Fit	10.8°	0.135	0.035
BEAMS			
K2K	?	?	?
MINOS	6°	0.04	0.01
	$\to 8^\circ$	$\to 0.08$	$\to 0.02$
CNGS	5°	0.03	0.008
	$\to 7^\circ$	$\to 0.06$	$\to 0.015$

$$P_{\mu\mu} \simeq 1 - \sin^2(2\theta_{23})\sin^2\left[\frac{\Delta_{atm}L}{2}\right] + \mathcal{O}\left[\left(\frac{\Delta_{sol}}{\Delta_{atm}}\right)\sin\theta_{13}\cos\delta\right]$$

Sensitivity loss due to $(\theta_{13} - \delta)$-correlations

Foreseeable bounds on θ_{13} (2)

EXP	θ_{13}	$\sin^2(2\theta_{13})$	$\sin^2\theta_{13}$
Global Fit	10.8°	0.135	0.035
REACT.			
Japan	4.5°	0.025	0.006
USA	3.5°	0.015	0.004
EU (D-CHOOZ)	5°	0.030	0.008

$$P_{ee} \simeq 1 - \sin^2(2\theta_{13})\sin^2\left[\frac{\Delta_{atm}L}{2}\right] + \mathcal{O}\left[\left(\frac{\Delta_{sol}}{\Delta_{atm}}\right)^2\right]$$

no sensitivity loss due to $(\theta_{13} - \delta)$-correlations

SYSTEMATIC DOMINATED!

Foreseeable bounds on θ_{13} (1)

EXP	θ_{13}	$\sin^2(2\theta_{13})$	$\sin^2\theta_{13}$
Global Fit	10.8°	0.135	0.035
SBEAMS			
T2K-I	2.2°	0.006	0.0015
(JHF)	$\to 3.3^\circ$	$\to 0.013$	$\to 0.0030$
NOνA	2°	0.005	0.0010
(NUMI-OA)	$\to 3.5^\circ$	$\to 0.015$	$\to 0.0040$

$$P_{\mu e} = s^2_{23}\sin^2(2\theta_{13})\sin^2\left[\frac{\Delta_{atm}L}{2}\right] +$$
$$\mathcal{O}\left[\left(\frac{\Delta_{sol}}{\Delta_{atm}}\right)\sin(2\theta_{13})\cos\delta\right] + \mathcal{O}\left[\left(\frac{\Delta_{sol}}{\Delta_{atm}}\right)\sin(2\theta_{13})\sin\delta\right]$$

Sensitivity loss due to $(\theta_{13}-\delta)$-correlations

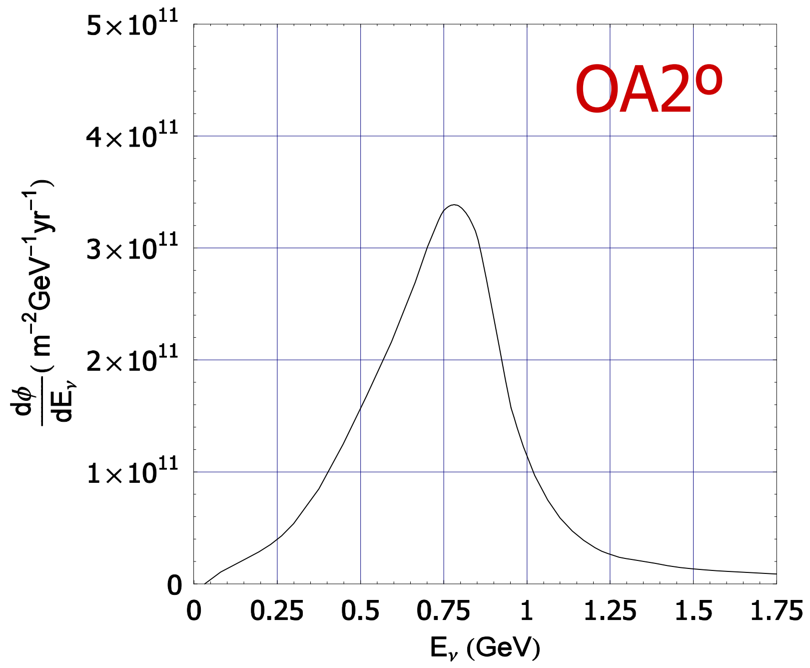
Around 2012...

After the wave of conventional beams and first generation superbeams, and of high-power reactors experiments, we will know something more on the PMNS matrix:

- mass differences $\Delta m^2_{atm}, \Delta m^2_{sol}$ at some %;

Fluxes

T2K-I

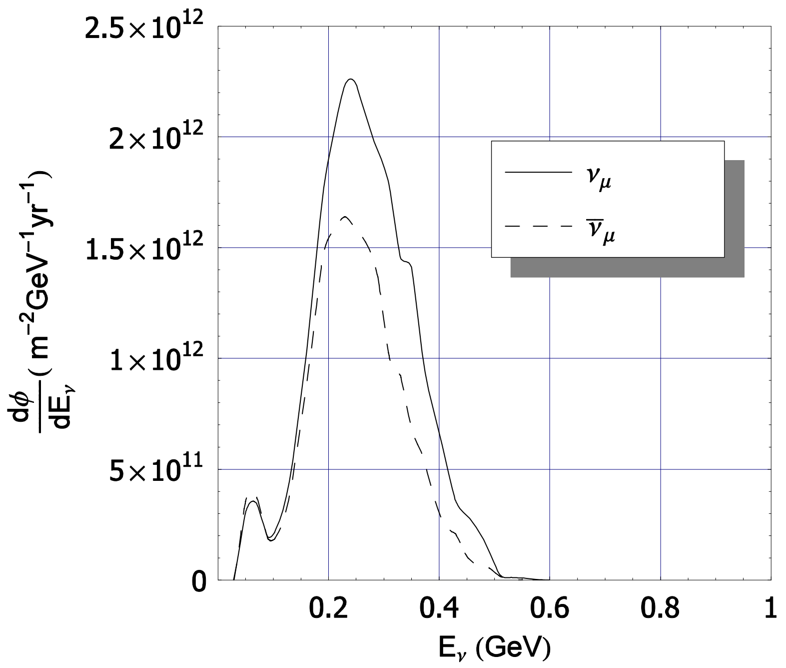


L=295Km

ν_μ flux from π^+ decay at $\langle E_\nu \rangle = 0.75GeV$

T2K fluxes courtesy of J.J. Gómez Cadenas

SPL



L=130Km

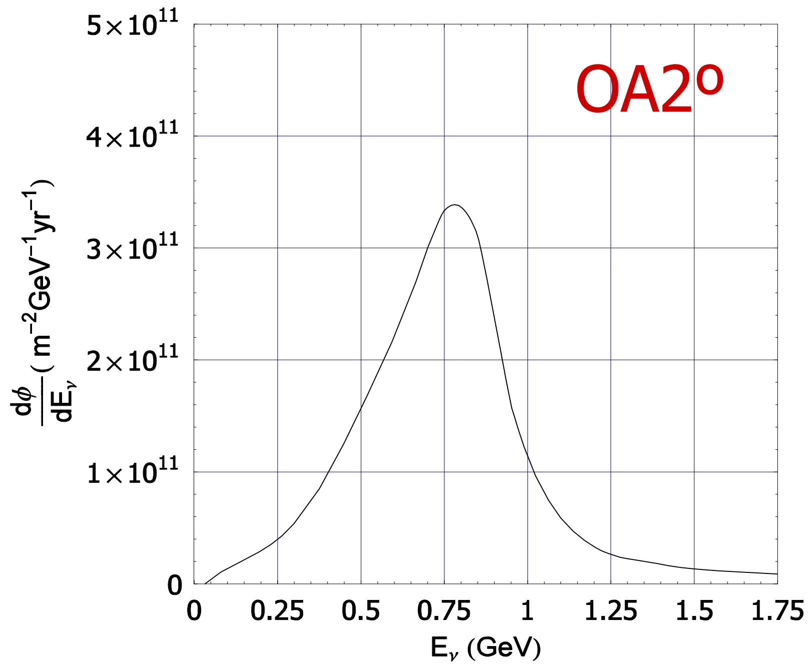
ν_μ flux from π^+ decay $\langle E_\nu \rangle = 0.27GeV$

$\overline{\nu}_\mu$ flux from π^- decay $\langle E_{\overline{\nu}} \rangle = 0.25GeV$

Old SPL fluxes courtesy of Gilardoni

Fluxes

T2K-I

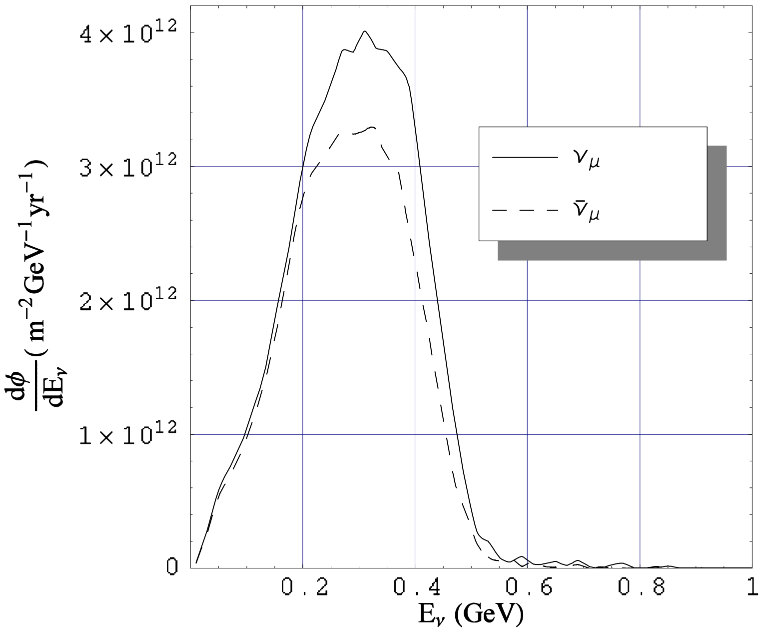


L=295Km

ν_μ flux from π^+ decay at $\langle E_\nu \rangle = 0.75 GeV$

T2K fluxes courtesy of J.J. Gómez Cadenas

SPL



L=130Km

ν_μ flux from π^+ decay $\langle E_\nu \rangle = 0.29 GeV$

$\bar{\nu}_\mu$ flux from π^- decay $\langle E_{\bar{\nu}} \rangle = 0.28 GeV$

New fluxes Campagne *et al.* hep-ex/0411062

Event Rates

T2K-I	B1	B2	B3	B4
No osc. N_μ	753	2228	2273	757
Signal N_μ	46	101	381	239

SPL	μ^-	μ^+
No osc. N_μ	24245	25467
Signal N_μ	1746	1614

4 energy bins of 200MeV
Between 0.4 – 1.2GeV

L=295Km

L=130Km

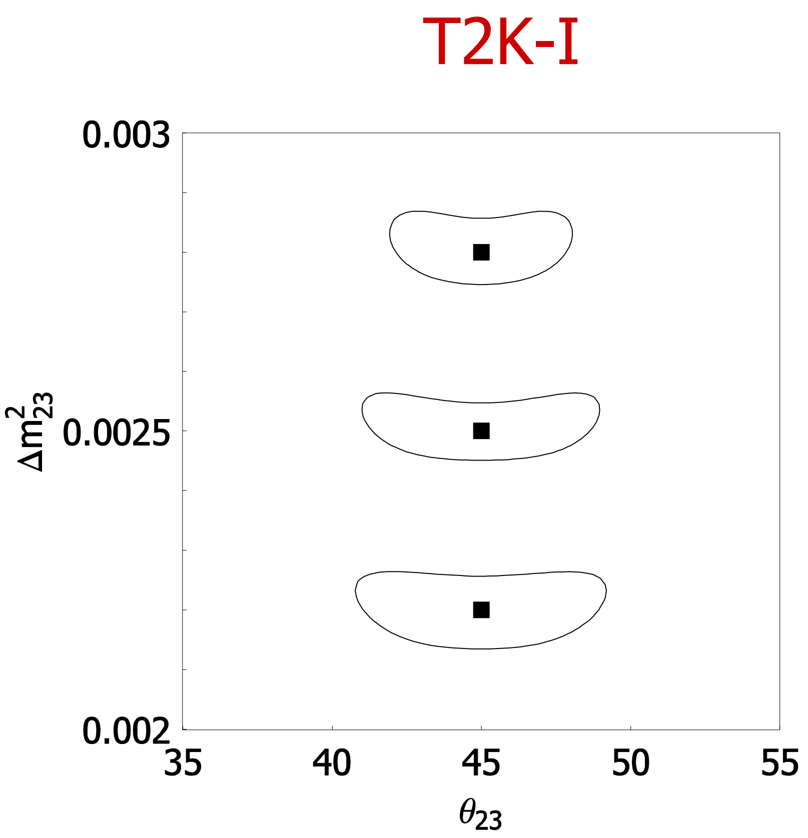
Statistics dominated

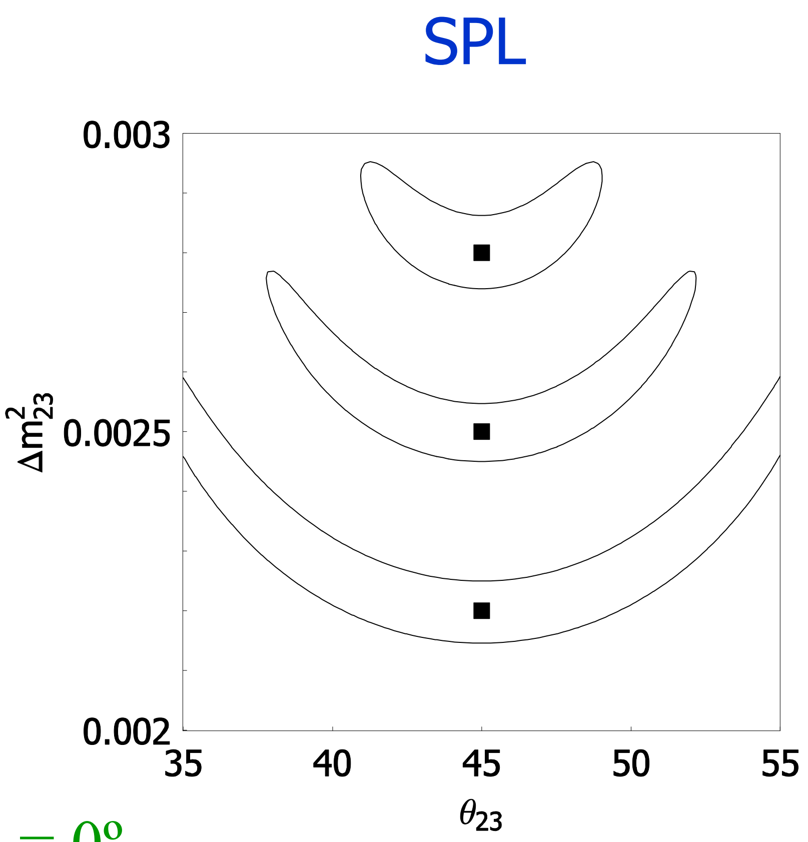
Systematic dominated

5yr ν_μ exposure with a 22.5Kt water cerenkov detector for T2K-I

2yr ν_μ + 8yr $\overline{\nu}_\mu$ exposure with a 440Kt water cerenkov detector for the SPL

The importance of energy resolution


T2K-I


SPL

$\theta_{13} = 0^o$

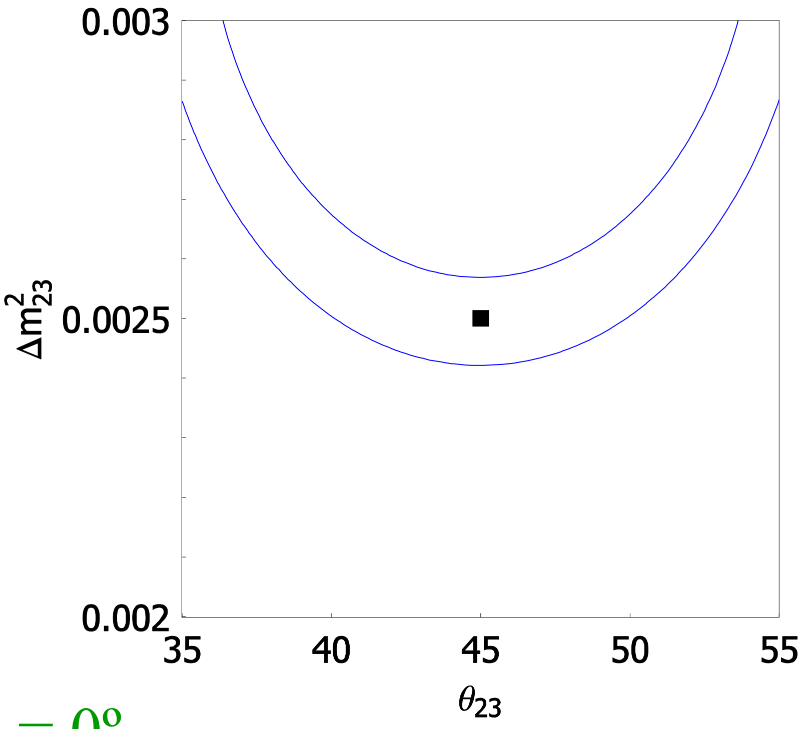
$\delta = 0^o$

90% CL contours
5% systematic error and backgrounds taken into account

The importance of energy resolution

T2K-I

SPL

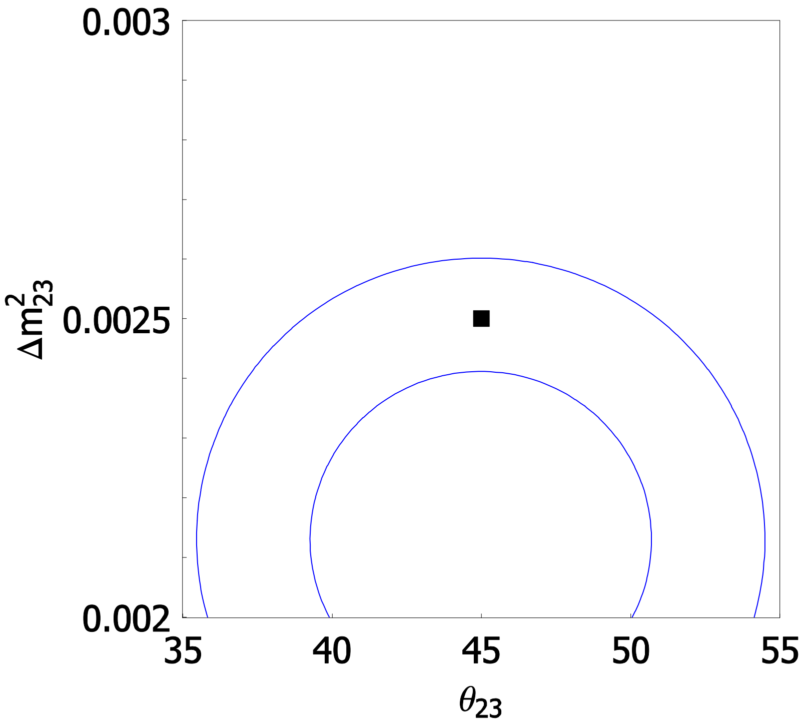


$\theta_{13} = 0^o$
$\delta = 0^o$

$\langle E_\nu \rangle = 0.27\text{GeV}$

The importance of energy resolution

T2K-I

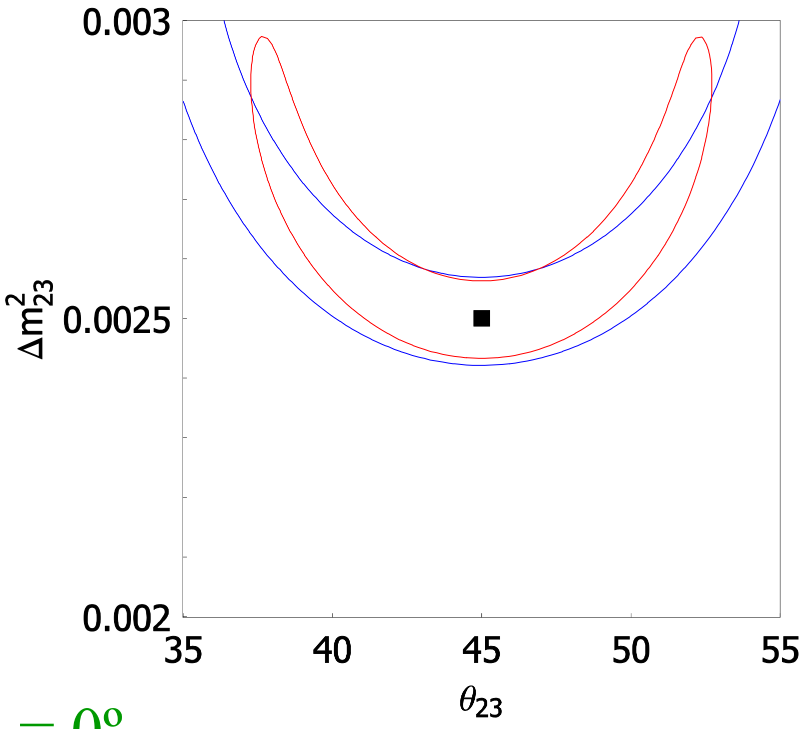


E1 = 0.4 - 0.6GeV

$\theta_{13} = 0^o$

$\delta = 0^o$

SPL

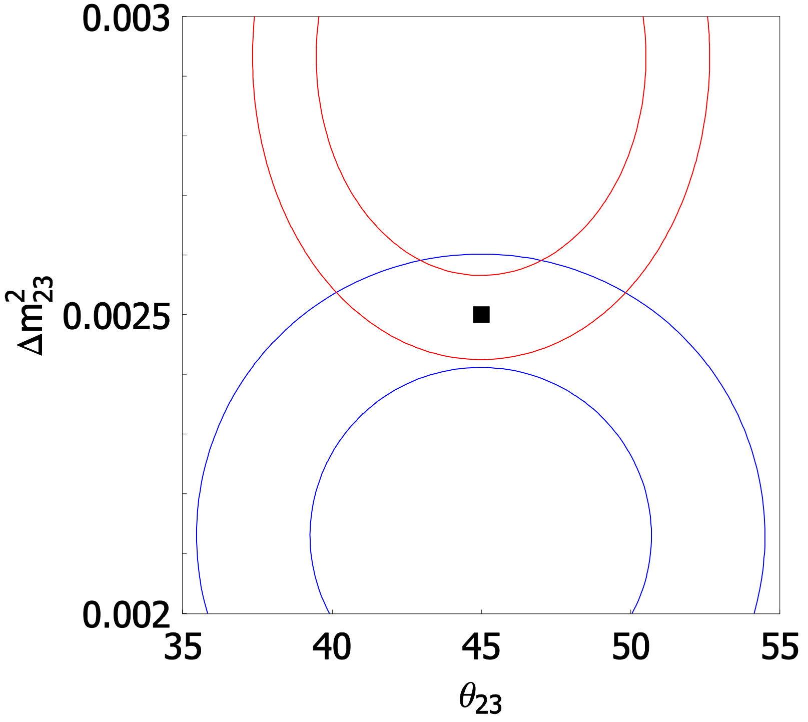


$\langle E_\nu \rangle = 0.27\text{GeV}$

$\langle E_{\bar{\nu}} \rangle = 0.25\text{GeV}$

The importance of energy resolution

T2K-I



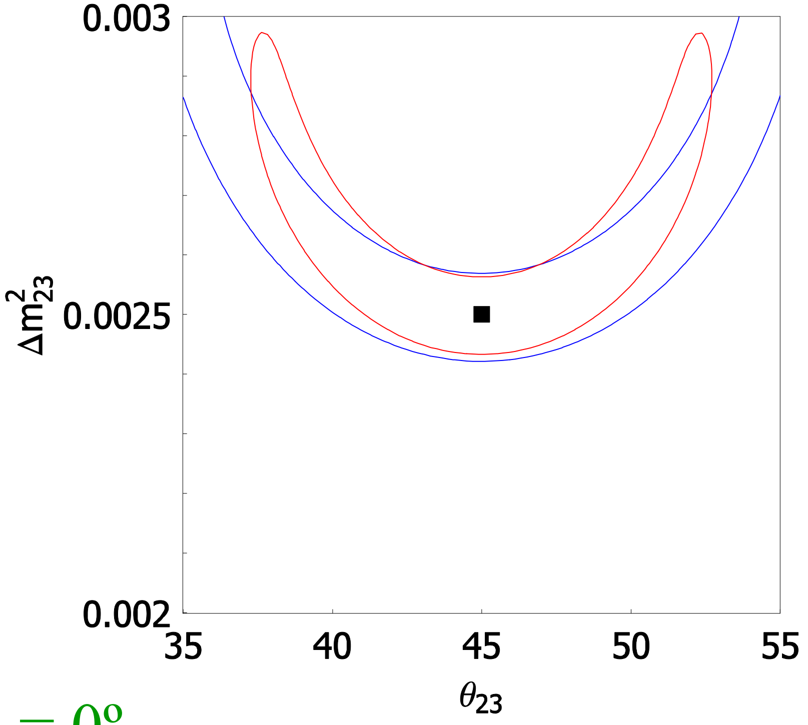
E1 = 0.4 - 0.6GeV

E2 = 0.6 - 0.8GeV

$\theta_{13} = 0^o$

$\delta = 0^o$

SPL

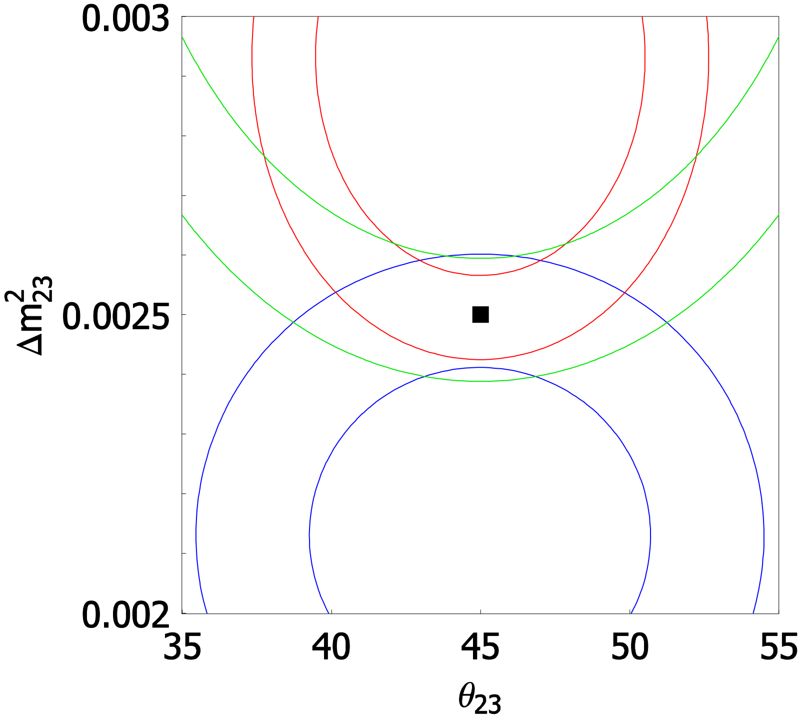


$\langle E_\nu \rangle = 0.27\text{GeV}$

$\langle E_{\bar{\nu}} \rangle = 0.25\text{GeV}$

The importance of energy resolution

T2K-I



E1 = 0.4 - 0.6GeV

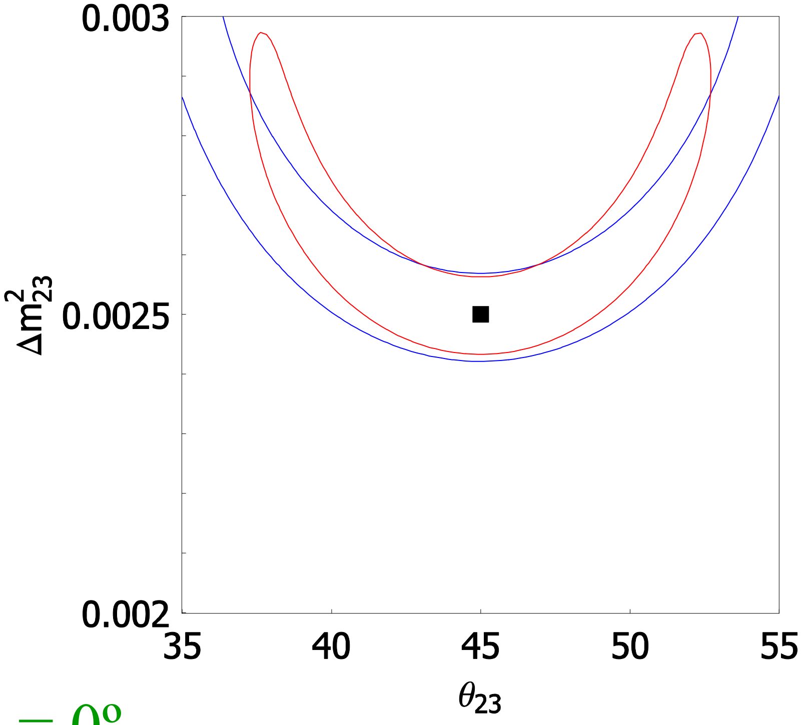
E2 = 0.6 - 0.8GeV

E3 = 0.8 - 1.0GeV

$\theta_{13} = 0^o$

$\delta = 0^o$

SPL

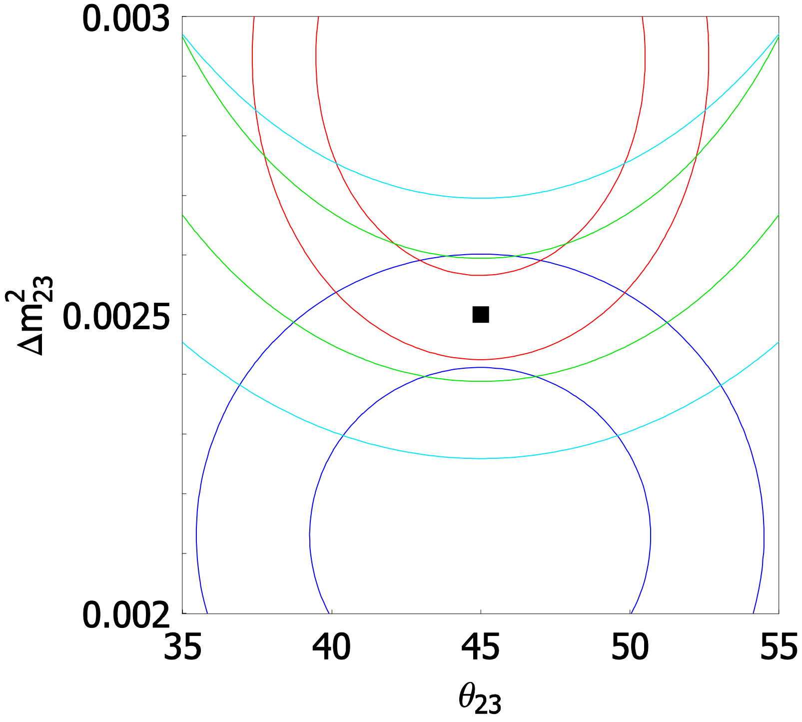


$\langle E_\nu \rangle = 0.27\text{GeV}$

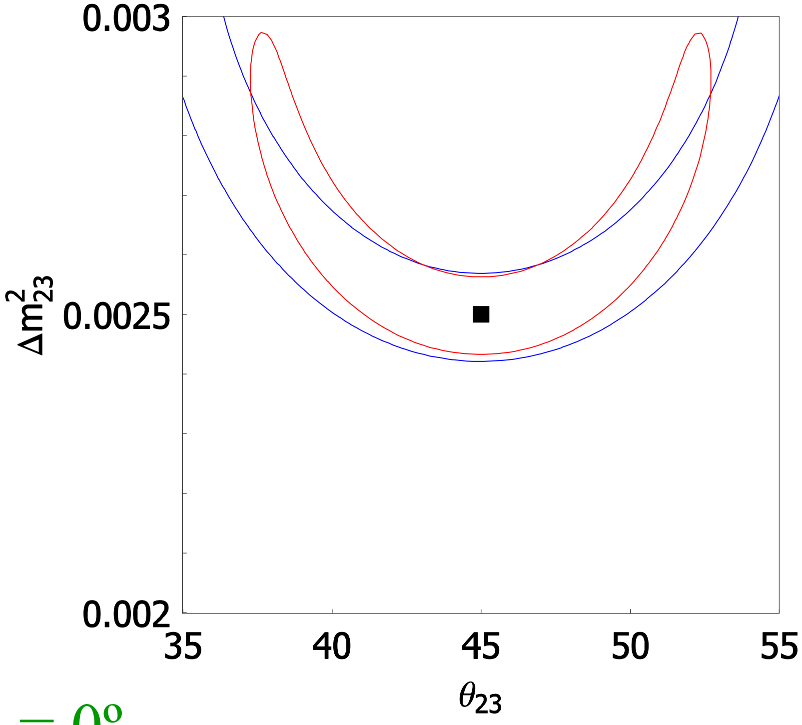
$\langle E_{\bar{\nu}} \rangle = 0.25\text{GeV}$

The importance of energy resolution

T2K-I



SPL



E1 = 0.4 - 0.6GeV

E2 = 0.6 - 0.8GeV

E3 = 0.8 - 1.0GeV

E4 = 1.0 - 1.2GeV

$\theta_{13} = 0^o$

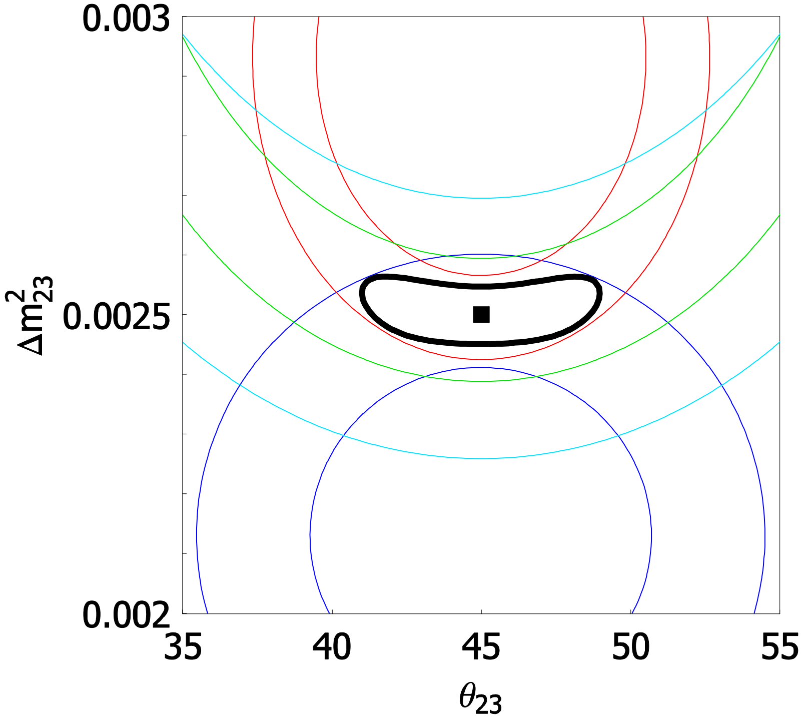
$\delta = 0^o$

$\langle E_\nu \rangle = 0.27\text{GeV}$

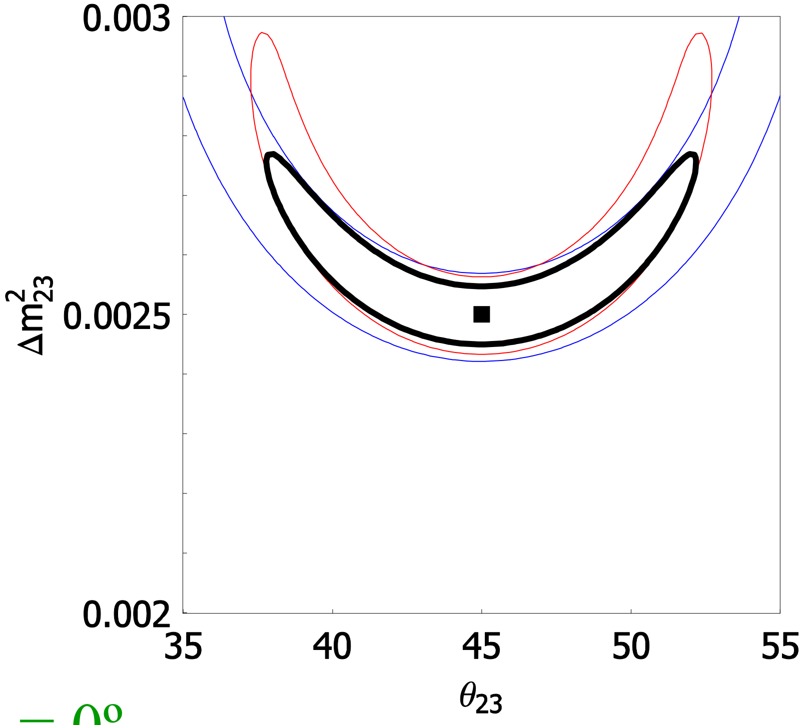
$\langle E_{\bar{\nu}} \rangle = 0.25\text{GeV}$

The importance of energy resolution

T2K-I



SPL



E1 = 0.4 - 0.6GeV
E2 = 0.6 - 0.8GeV
E3 = 0.8 - 1.0GeV
E4 = 1.0 - 1.2GeV

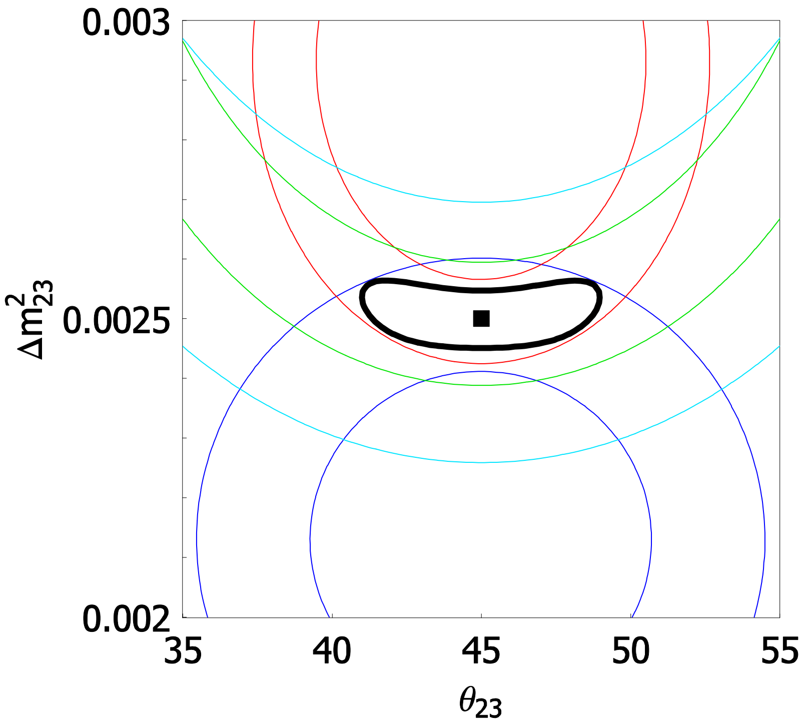
$\theta_{13} = 0^o$
$\delta = 0^o$

$\langle E_\nu \rangle = 0.27\text{GeV}$

$\langle E_{\bar{\nu}} \rangle = 0.25\text{GeV}$

The importance of energy resolution

T2K-I



$E1 = 0.4 - 0.6$GeV

$E2 = 0.6 - 0.8$GeV

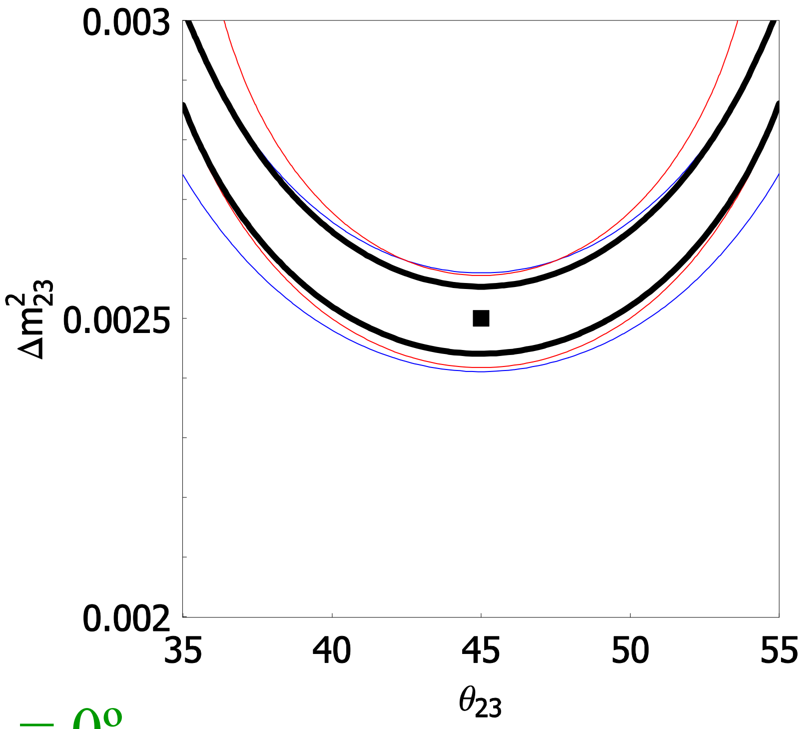
$E3 = 0.8 - 1.0$GeV

$E4 = 1.0 - 1.2$GeV

$\theta_{13} = 0^o$

$\delta = 0^o$

SPL-new



$\langle E_\nu \rangle = 0.29$GeV

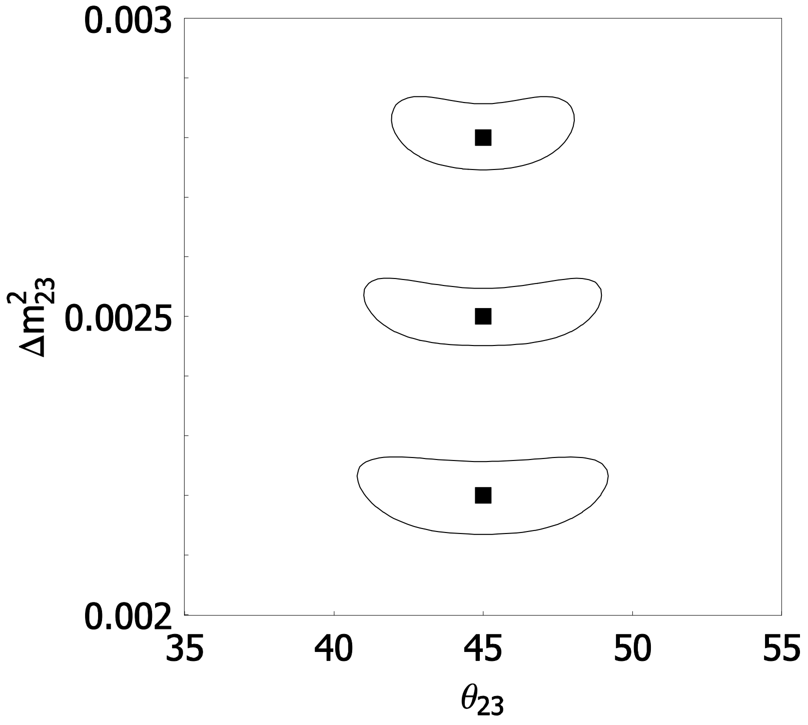
$\langle E_{\bar{\nu}} \rangle = 0.28$GeV

The sign degeneracy

Input:

$\theta_{13} = 0^o$

$\delta = 0^o$



$$P(\nu_\mu \to \nu_\mu) = 1 - (\sin^2 2\theta_{23}) \sin^2\left(\frac{\Delta_{atm} L}{2}\right)$$

$$+ O\left(\frac{\Delta_{sol} L}{2}\right)$$

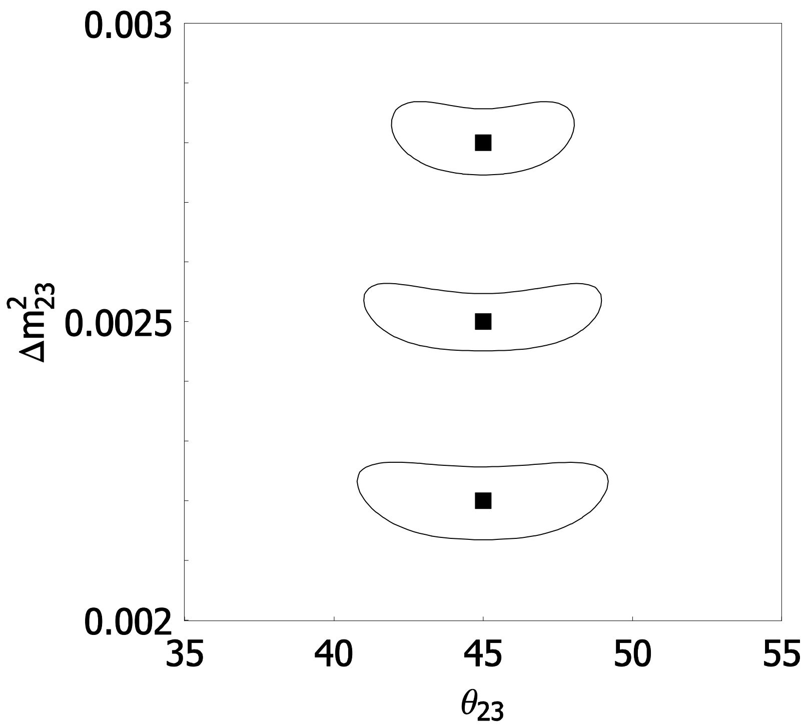
$$+ O\left(\frac{\Delta_{sol} L}{2}\right)^2$$

The sign degeneracy

Input:

$\theta_{13} = 0^o$

$\delta = 0^o$



$$P(\nu_\mu \to \nu_\mu) = 1 - (\sin^2 2\theta_{23}) \sin^2\left(\frac{\Delta_{atm} L}{2}\right)$$

$$- \left(\frac{\Delta_{sol} L}{2}\right) [s_{12}^2 \sin^2 2\theta_{23}] \boxed{\sin(\Delta_{atm} L)}$$

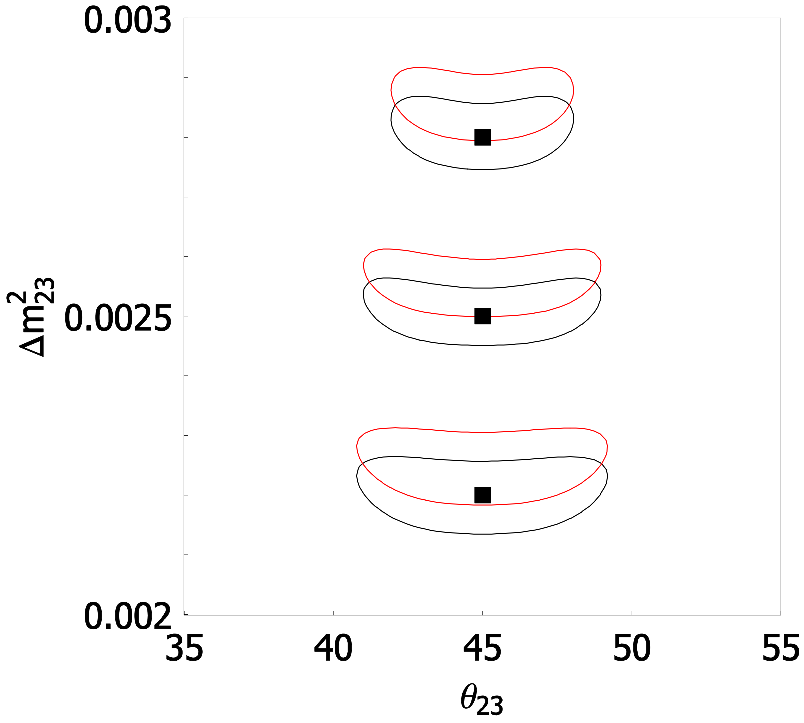
$$+ O\left(\frac{\Delta_{sol} L}{2}\right)^2$$

The sign degeneracy

Input:

$\theta_{13} = 0^{o}$

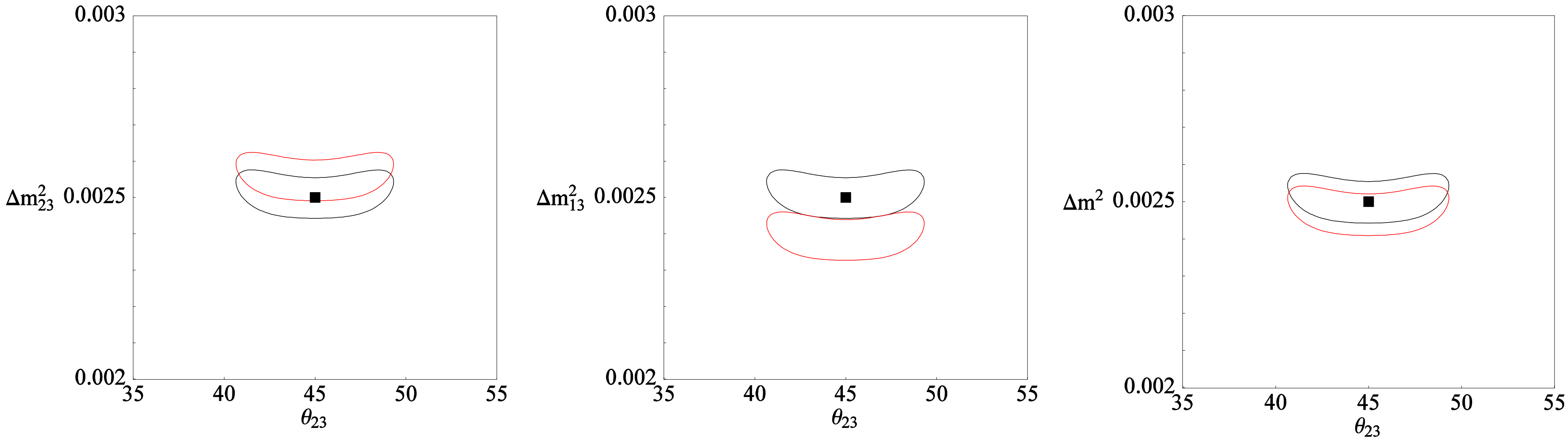
$\delta = 0^{o}$



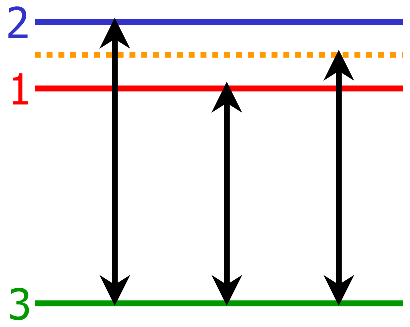
Fit assuming inverted hierarchy

$$P(\nu_\mu \to \nu_\mu) = 1 - (\sin^2 2\theta_{23}) \sin^2\left(\frac{\Delta_{atm} L}{2}\right) - \left(\frac{\Delta_{sol} L}{2}\right)[s_{12}^2 \sin^2 2\theta_{23}] \boxed{\sin(\Delta_{atm} L)} + O\left(\frac{\Delta_{sol} L}{2}\right)^2$$

The sign degeneracy



Normal



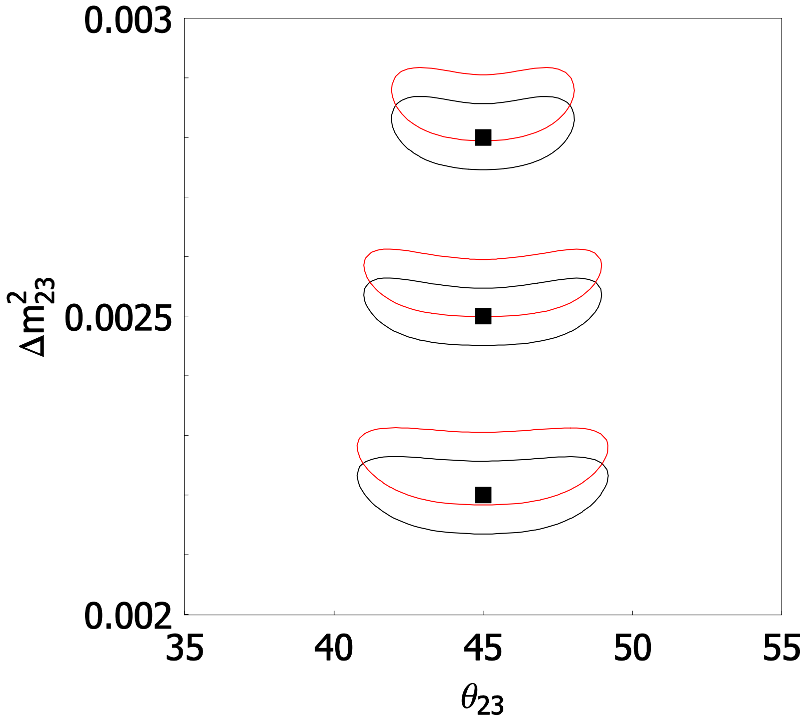
Inverted

The octant degeneracy

Input:

$\theta_{13} = 0^{o}$

$\delta = 0^{o}$



$$P(\nu_\mu \to \nu_\mu) = 1 - \boxed{\sin^2 2\theta_{23}}\,\sin^2\left(\frac{\Delta_{atm} L}{2}\right)$$

$$- \left(\frac{\Delta_{sol} L}{2}\right)\left[s_{12}^2 \boxed{\sin^2 2\theta_{23}}\right]\sin(\Delta_{atm} L)$$

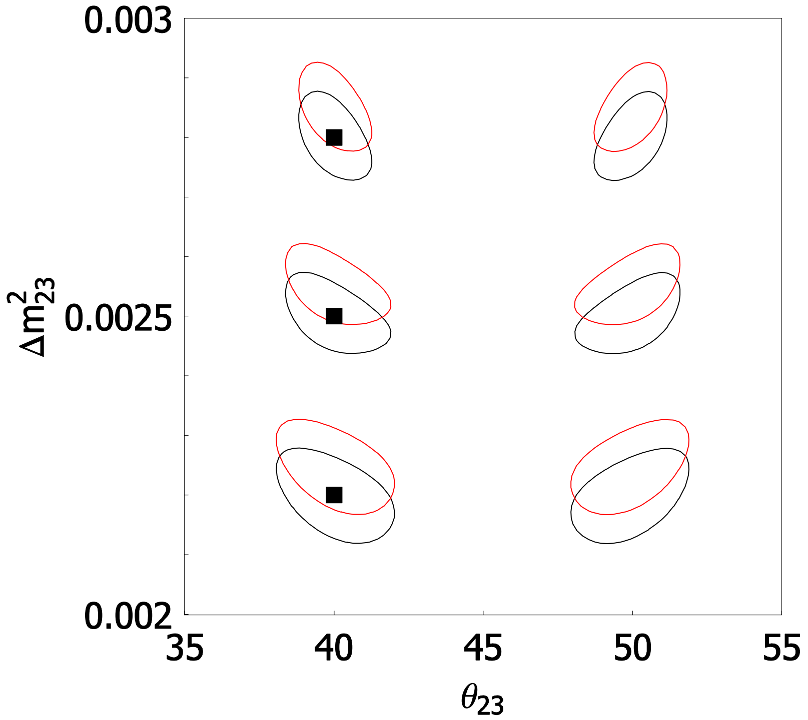
$$+ O\left(\frac{\Delta_{sol} L}{2}\right)^2$$

The octant degeneracy

Input:

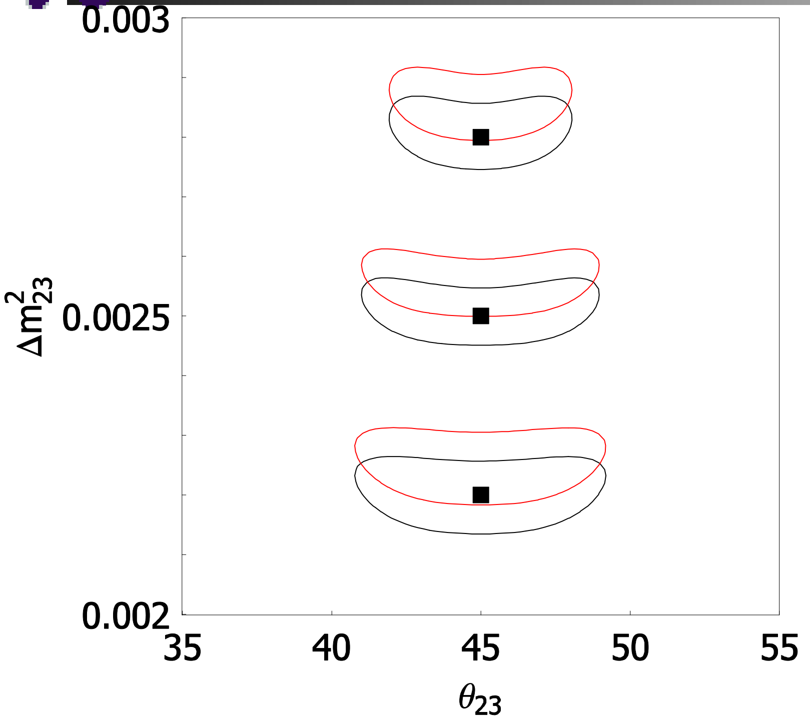
$\theta_{13} = 0^{o}$

$\delta = 0^{o}$



$$P(\nu_\mu \to \nu_\mu) = 1 - \boxed{\sin^2 2\theta_{23}}\, \sin^2\left(\frac{\Delta_{atm} L}{2}\right) - \left(\frac{\Delta_{sol} L}{2}\right)\left[s_{12}^2 \boxed{\sin^2 2\theta_{23}}\right] \sin(\Delta_{atm} L) + O\left(\frac{\Delta_{sol} L}{2}\right)^2$$

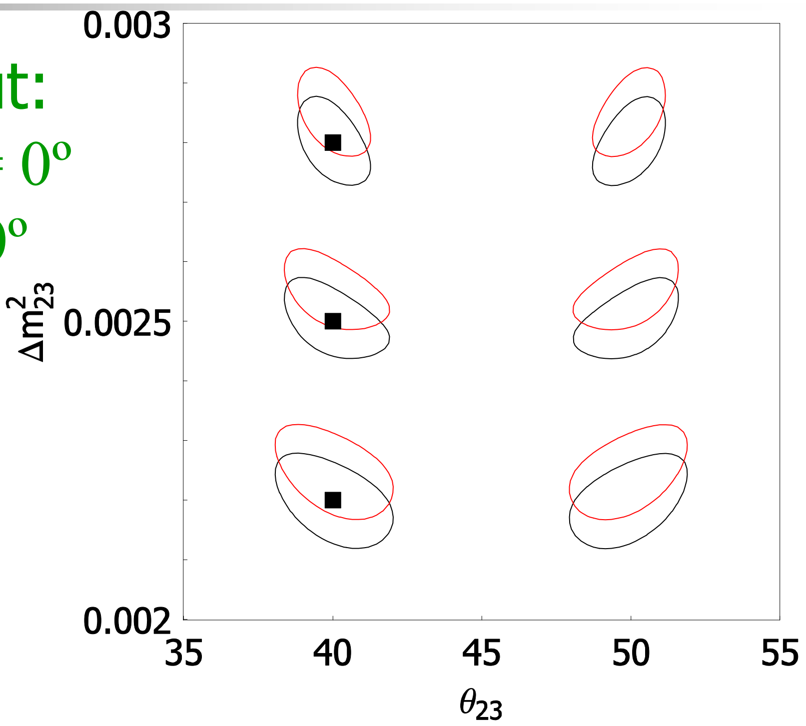
The effect of θ_{13}



Input:

$\theta_{13} = 0^o$

$\delta = 0^o$

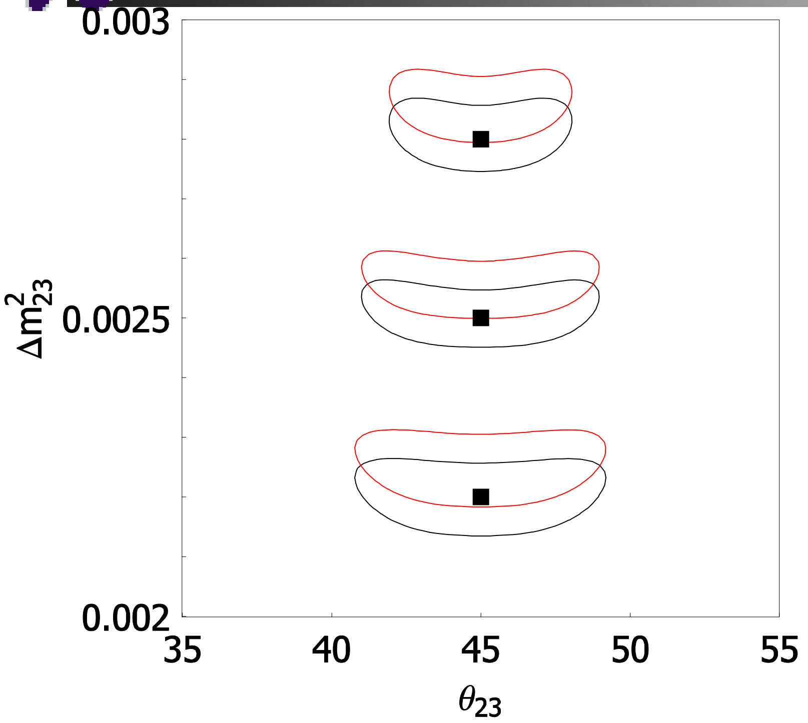


$$P(\nu_\mu \to \nu_\mu) = 1 - (\sin^2 2\theta_{23}) \sin^2\left(\frac{\Delta_{atm} L}{2}\right)$$

$$- \left(\frac{\Delta_{sol} L}{2}\right) [s_{12}^2 \sin^2 2\theta_{23}] \sin(\Delta_{atm} L)$$

$$+ O\left(\frac{\Delta_{sol} L}{2}\right)^2$$

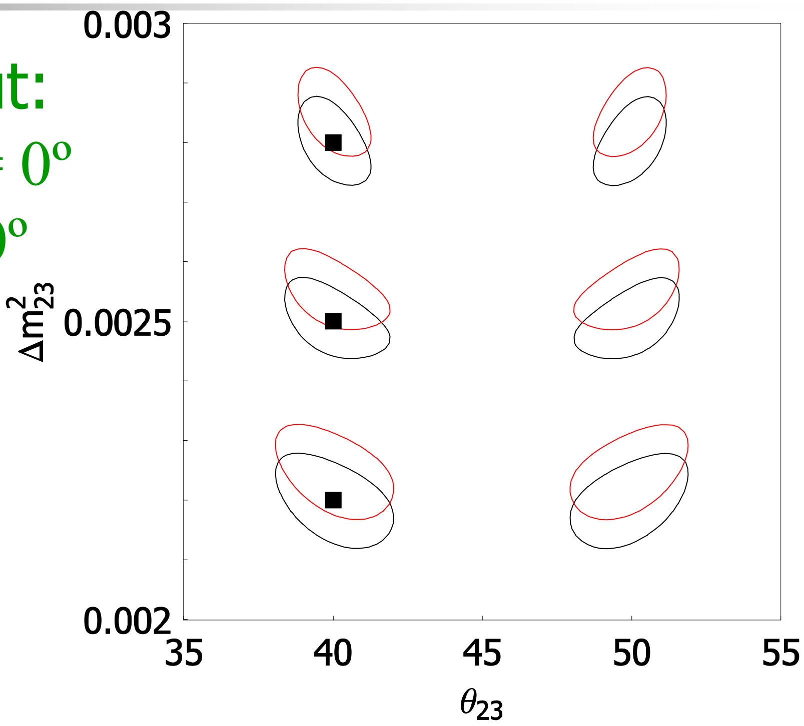
The effect of θ_{13}



Input:

$\theta_{13} = 0^o$

$\delta = 0^o$



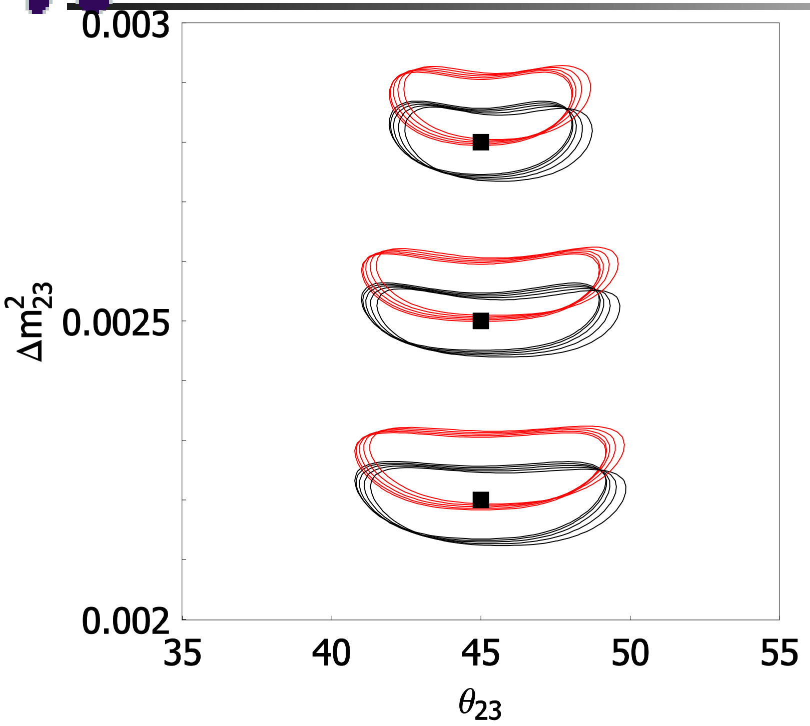
Assuming $\theta_{13} = 0^o$

$$P(\nu_\mu \to \nu_\mu) = 1 - (\sin^2 2\theta_{23} - s^2_{23} \sin^2 2\theta_{13} \cos^2 2\theta_{23}) \sin^2\left(\frac{\Delta_{atm} L}{2}\right)$$

$$- \left(\frac{\Delta_{sol} L}{2}\right) [s^2_{12} \sin^2 2\theta_{23} + \tilde{J} s^2_{23} \cos\delta] \sin(\Delta_{atm} L)$$

$$+ O\left(\frac{\Delta_{sol} L}{2}\right)^2$$

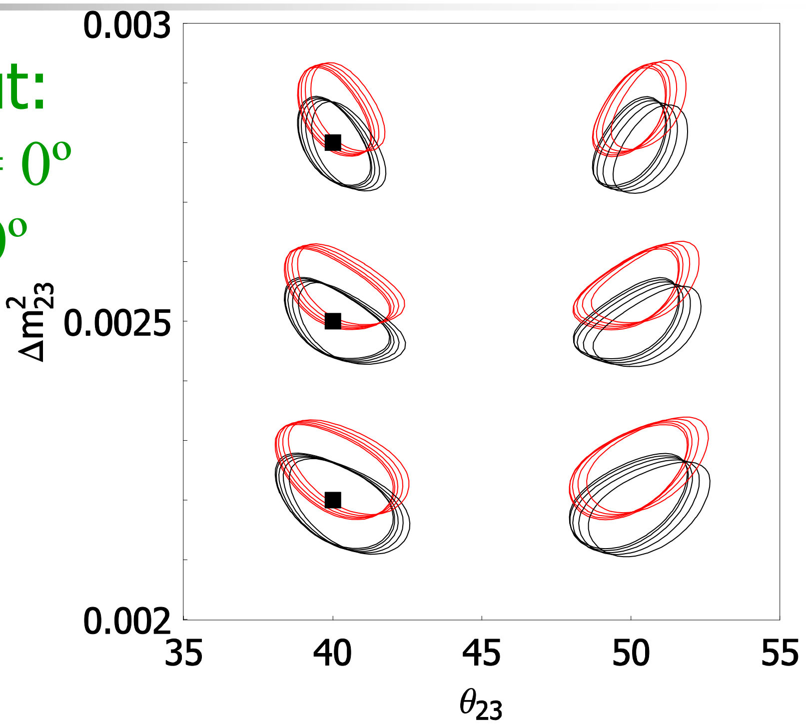
The effect of θ_{13}



Input:

$\theta_{13} = 0^{\circ}$

$\delta = 0^{\circ}$



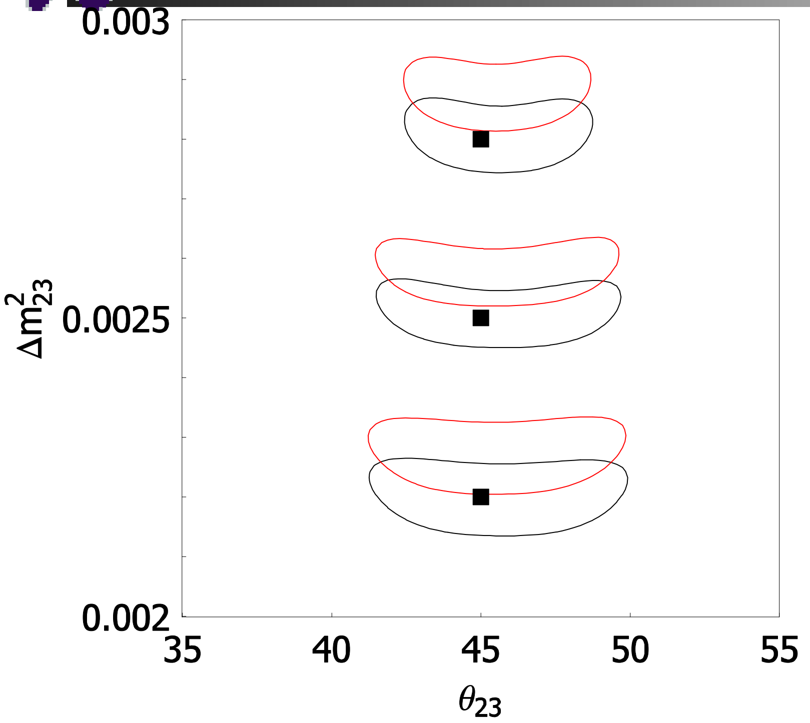
Assuming $\theta_{13} =$ 0°, 2°, 4°, 6°, 8°

$$P(\nu_\mu \to \nu_\mu) = 1 - \left(\sin^2 2\theta_{23} - \boxed{s^2_{23}} \sin^2 2\theta_{13} \cos^2 2\theta_{23}\right) \sin^2\left(\frac{\Delta_{atm} L}{2}\right)$$

$$- \left(\frac{\Delta_{sol} L}{2}\right)\left[s^2_{12} \sin^2 2\theta_{23} + J \boxed{s^2_{23}} \cos\delta\right] \sin(\Delta_{atm} L)$$

$$+ O\left(\frac{\Delta_{sol} L}{2}\right)^2$$

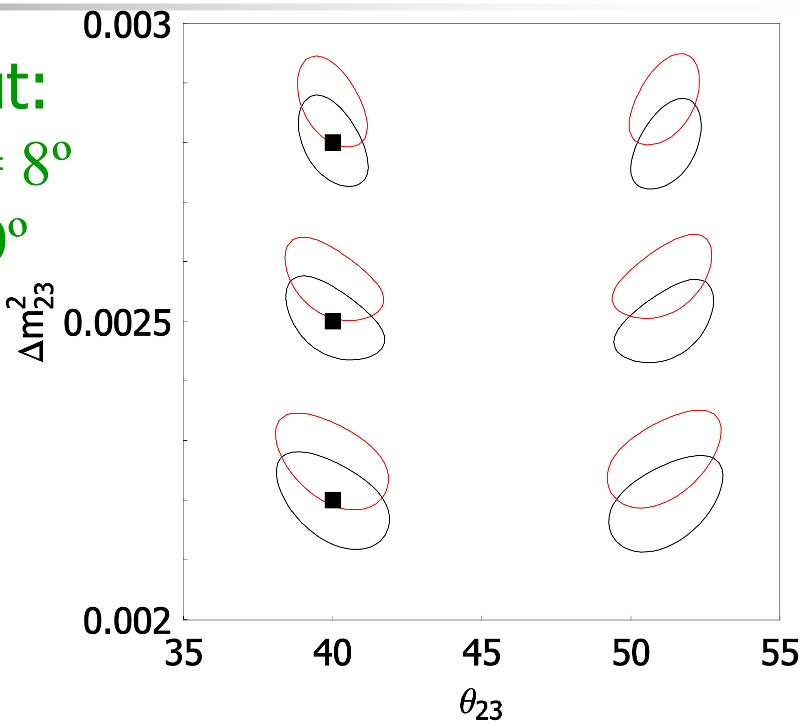
The effect of δ



Input:

$\theta_{13} = 8^o$

$\delta = 0^o$



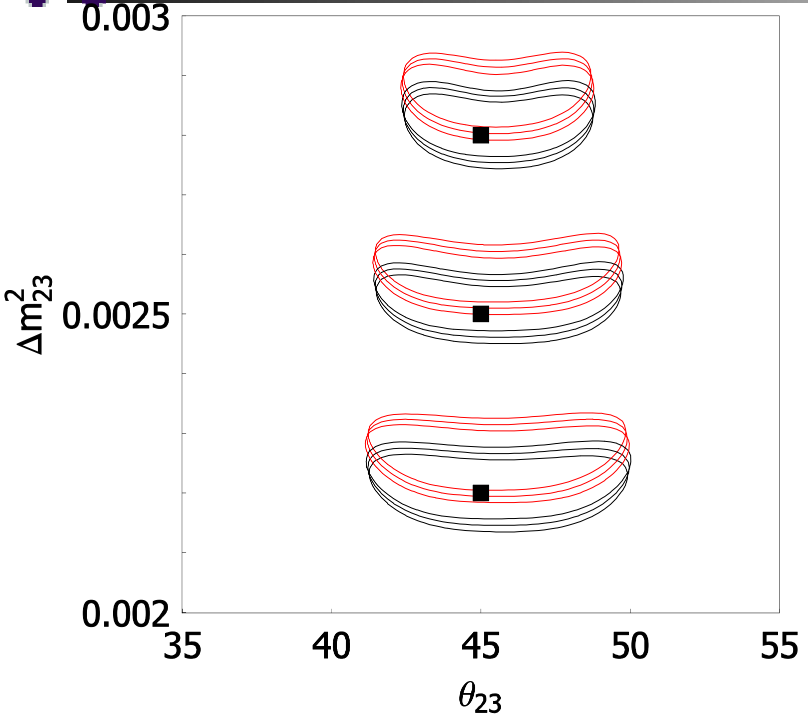
Assuming $\delta = 0^o$

$$P(\nu_\mu \to \nu_\mu) = 1 - (\sin^2 2\theta_{23} - s^2_{23} \sin^2 2\theta_{13} \cos^2 2\theta_{23}) \sin^2\left(\frac{\Delta_{atm} L}{2}\right)$$

$$- \left(\frac{\Delta_{sol} L}{2}\right) [s^2_{12} \sin^2 2\theta_{23} \boxed{+ \tilde{J} s^2_{23} \cos\delta}] \sin(\Delta_{atm} L)$$

$$+ O\left(\frac{\Delta_{sol} L}{2}\right)^2$$

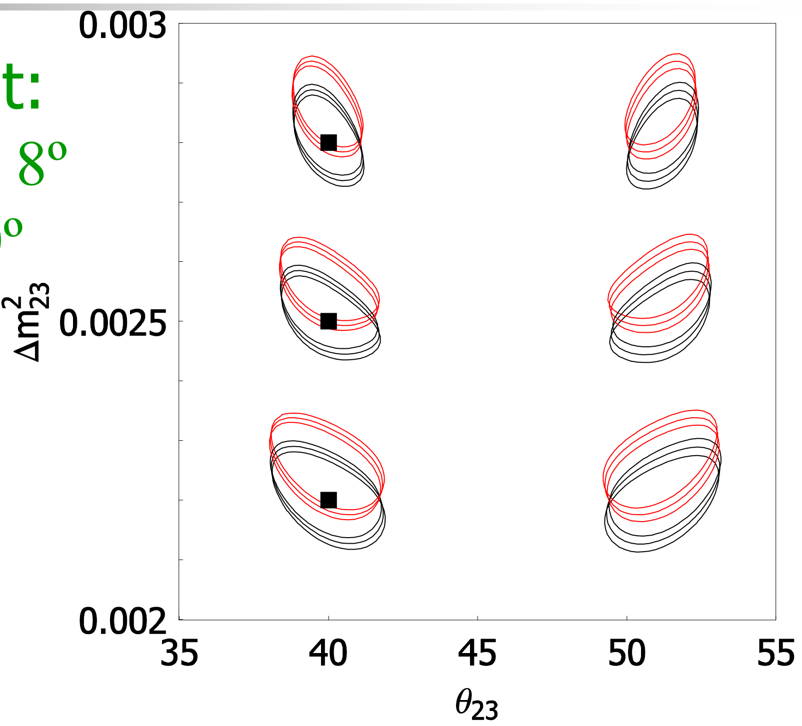
The effect of δ



Input:

$\theta_{13} = 8^\circ$

$\delta = 0^\circ$



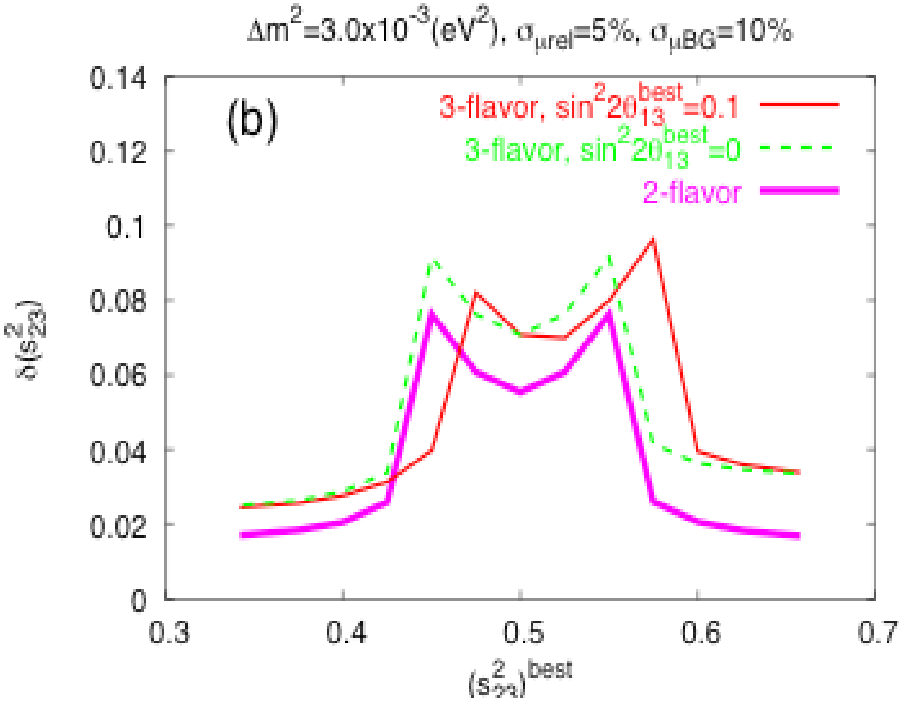
Assuming $\delta = 0^\circ, 90^\circ, 180^\circ$

$$P(\nu_\mu \to \nu_\mu) = 1 - (\sin^2 2\theta_{23} - s_{23}^2 \sin^2 2\theta_{13} \cos^2 2\theta_{23}) \sin^2\left(\frac{\Delta_{atm} L}{2}\right)$$

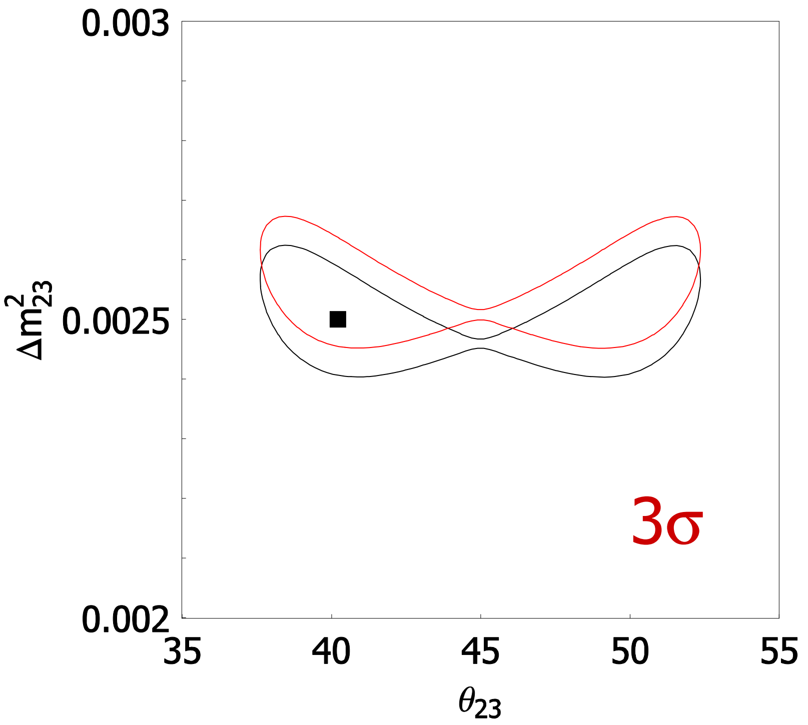
$$- \left(\frac{\Delta_{sol} L}{2}\right) [s_{12}^2 \sin^2 2\theta_{23} \boxed{+ \tilde{J} s_{23}^2 \cos\delta}] \sin(\Delta_{atm} L)$$

$$+ O\left(\frac{\Delta_{sol} L}{2}\right)^2$$

T2K-I errors revised



Minakata *et al.* hep-ph/0406073



$\Delta m^2 = (1.7 - 3.5)\cdot10^{-3}$ eV^2

$\sin^2 2\theta > 0.9$ $\tan^2\theta = 0.53 - 2.04$

$\Delta m^2 = (2.43 - 2.60)\cdot10^{-3}$ eV^2

$\sin^2 2\theta > 0.97$ $\tan^2\theta = 0.73 - 1.39$

$\Delta m^2 = (-2.63 - -2.49)\cdot10^{-3}$ eV^2

$\Delta m^2 = (2.42 - 2.61)\cdot10^{-3}$ eV^2

$\sin^2 2\theta = 0.94 - 0.99$

$\tan^2\theta = 0.62 - 0.85, 1.21 - 1.66$

$\Delta m^2 = (-2.64 - -2.47)\cdot10^{-3}$ eV^2

Around 2012...

After the wave of conventional beams and first generation superbeams, and of high-power reactors experiments, we will know something more on the PMNS matrix:

- ▷ mass differences $\Delta m^2_{atm}, \Delta m^2_{sol}$ at some %;
- ▷ mixing angles θ_{12}, θ_{23} at some %;

Around 2012...

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- ▷ the value of θ_{13}, if large.

Around 2012...

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- ▷ mass differences $\Delta m^2_{atm}, \Delta m^2_{sol}$ at some %;
- ▷ mixing angles θ_{12}, θ_{23} at some %;
- ▷ the value of θ_{13}, if large.

Precision measurements of LEPTONIC MIXING will start with the next-to-next generation experiments, using SuperBeams or BetaBeams with 1 Mton Water Čerenkov or/and the Neutrino Factory.

An intermediate phase?

After T2K and NOνA, we will face a forking path:

★ $\nu_\mu \to \nu_e$ oscillation has been observed!
A good option: increase detector mass,
same source: T2-HK or SPL+UNO
(really a good option?)

- No signal has been observed: $\theta_{13} \leq 3^\circ - 4^\circ$!
  Go to new sources:
  Neutrino Factory or the Beta-Beam.

I will use the CERN SPL project to illustrate the problems we face to measure (θ_{13}, δ) in the intermediate phase.
T2-HK gives similar results.

Appearance Signal at a SB

$$\boxed{\pi^+} \rightarrow \begin{cases} \boxed{\mu^+ \rightarrow \bar{\nu}_\mu, \nu_e \rightarrow e^-} & \textit{Background} \\ \boxed{\nu_\mu \rightarrow \nu_e \rightarrow e^-} & \textit{Signal} \end{cases}$$

The oscillation probability is

$$P^{\pm}_{\mu e} \simeq X_{\pm} \sin^2(2\,\theta_{13})$$

$$+Y_{\pm} \cos\left(\delta \pm \frac{\Delta_{atm} L}{2}\right) \cos\theta_{13} \sin(2\,\theta_{13})$$

$$+Z + \ldots$$

The Coefficients

For the golden channel we have:

$$\left\{\begin{array}{lcl} X_\pm & = & \Delta^2_{atm} \times f_X^\pm\,(\theta_{23}, A, L, E_\nu) \\ Y_\pm & = & \Delta_{sol} \times \Delta_{atm} \times f_Y^\pm\,(\theta_{12}, \theta_{23}, A, L, E_\nu) \\ Z & = & \Delta^2_{sol} \times f_Z\,(\theta_{12}, \theta_{23}, A, L, E_\nu) \end{array}\right.$$

($+$ neutrinos, $-$ antineutrinos)

The (θ_{13}, δ) correlation

The number of signal electrons is:

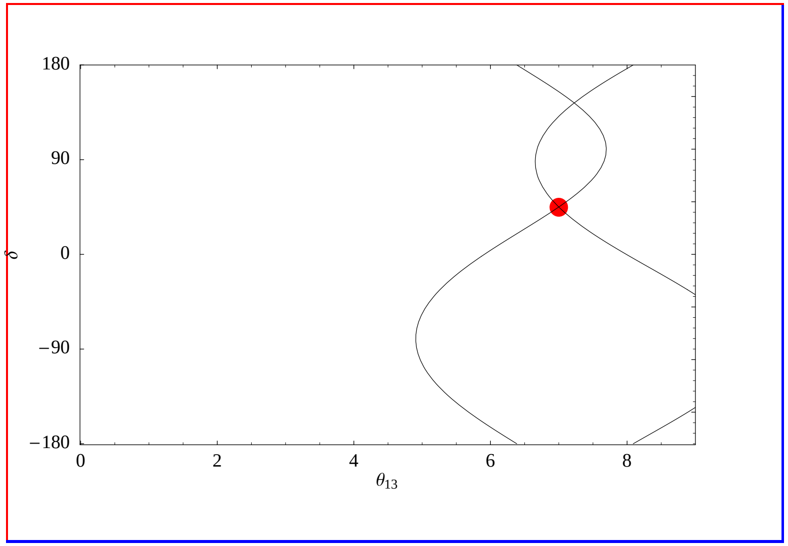
$$N_{e^-}(\bar\theta_{13}, \bar\delta) = \left\{ \epsilon_e \otimes \sigma_{\nu_e} \otimes P^{+}_{\mu e}(\bar\theta_{13}, \bar\delta) \otimes \Phi_{\nu_\mu} \right\}_{E}^{E+\Delta E}$$

$$\boxed{N^i_{\pm}(\bar\theta_{13}, \bar\delta) = N^i_{\pm}(\theta_{13}, \delta)}$$

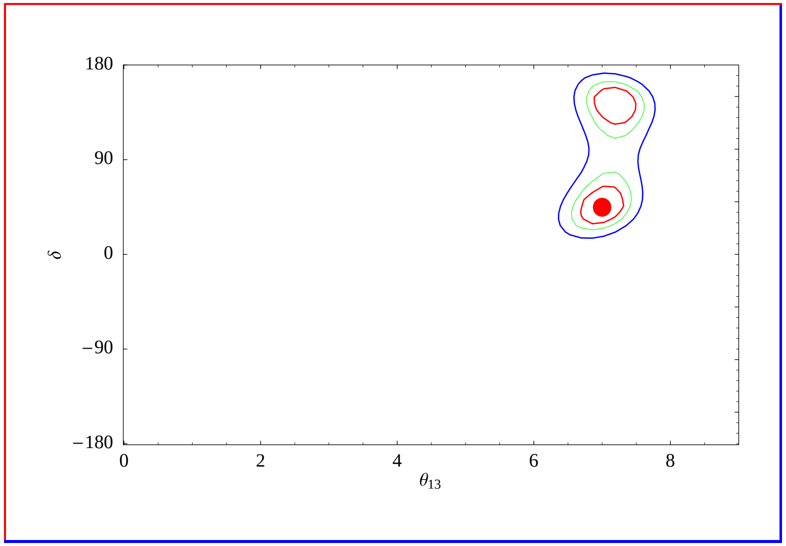
By changing (θ_{13}, δ) accordingly,
curves are drawn in the (θ_{13}, δ) plane.

Degeneracy in (θ_{13}, δ) at the SPL

2 years for π^+ and 8 years for π^-



$\Rightarrow$



L = 130 Km, $\bar{E}_{\nu_\mu} = 0.27$ GeV, $\bar{E}_{\bar{\nu}_\mu} = 0.25$ GeV

Input parameters: $\bar{\theta}_{13} = 7°, \bar{\delta} = 45°$

The (θ_{13}, δ) correlation (2)

The number of signal electrons is:

$$N_{e^-}(\bar\theta_{13}, \bar\delta) = \left\{ \epsilon_e \otimes \sigma_{\nu_e} \otimes P^+_{\mu e}(\bar\theta_{13}, \bar\delta) \otimes \Phi_{\nu_\mu} \right\}_E^{E+\Delta E}$$

$$N^i_\pm(\bar\theta_{13}, \bar\delta, \bar s_{atm}, \bar s_{oct}) = N^i_\pm(\theta_{13}, \delta, s_{atm}, s_{oct})$$

where

$$\begin{cases} s_{atm} & = & sign(\Delta m^2_{atm}) = \pm 1 \\ s_{oct} & = & sign(\tan 2\theta_{23}) = \pm 1 \end{cases}$$

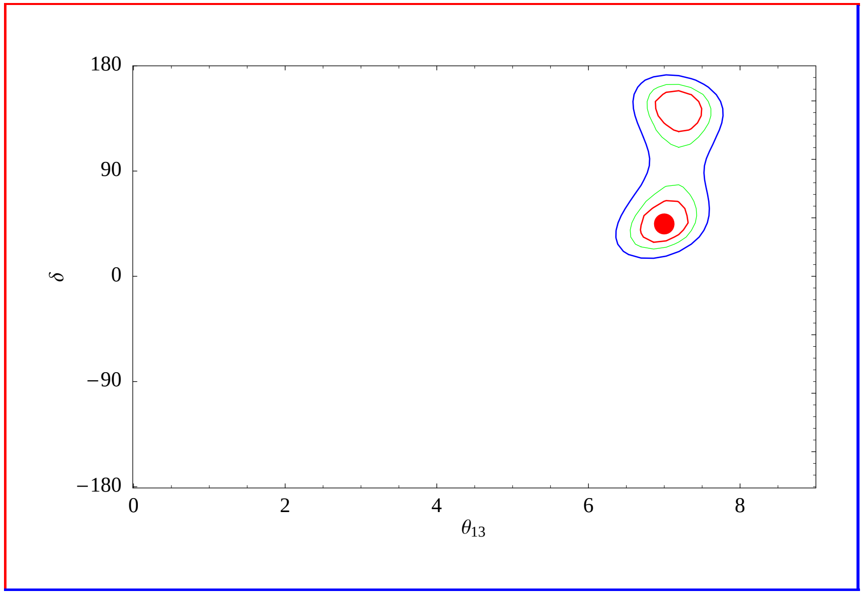
Of other clones

As a first step:

- ▷ $\theta_{23} = 45°$
- ▷ Sign of Δ_{atm} fixed

J. Burguet-Castell *et al.*, hep-ph/0103258

The intrinsic clone



Of other clones

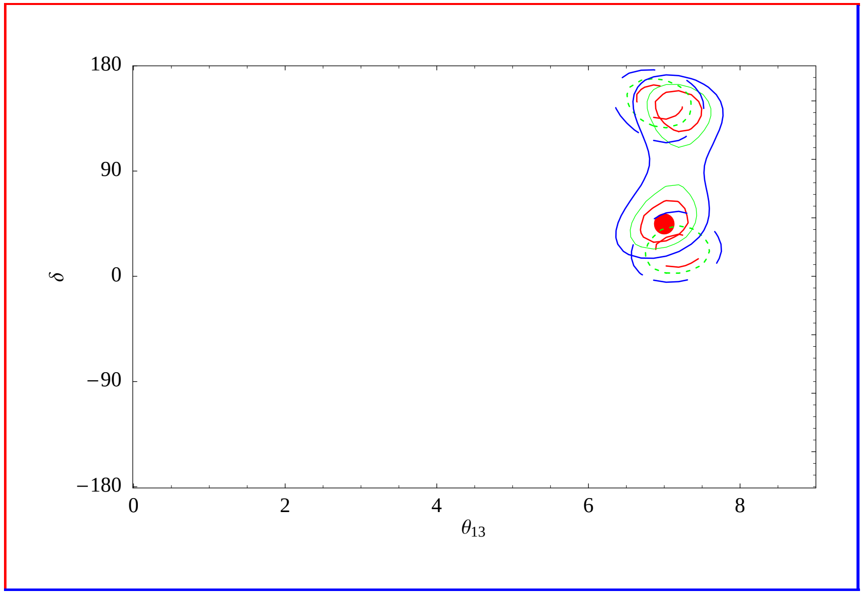
As a third step:

- ▷ $\theta_{23} = 45°$
- ▷ Sign of Δ_{atm} variable

H. Minakata, H. Nunokawa, hep-ph/0108085

One more ambiguity:

- ▷ the sign clones

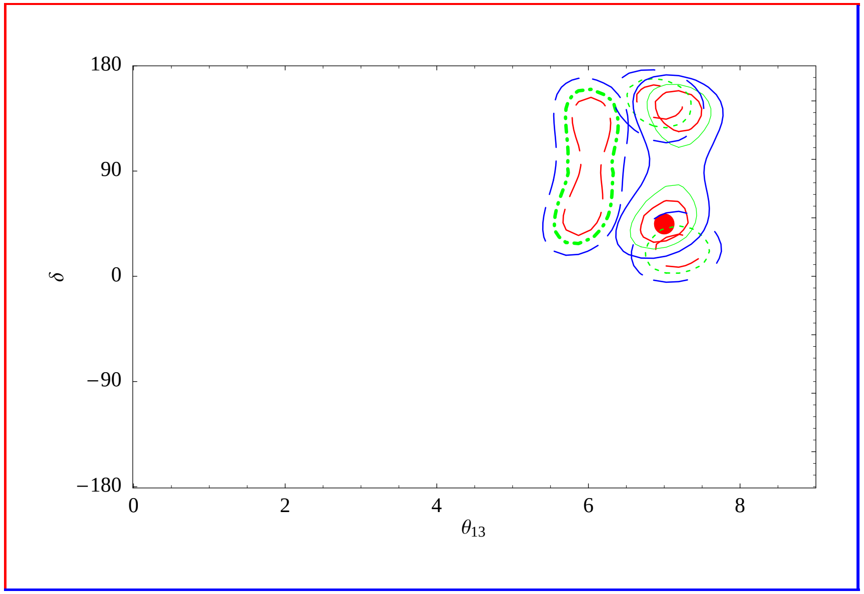


Of other clones

As a second step:

- ▷ $\theta_{23} = 40^\circ$ or $\theta_{23} = 50^\circ$
- ▷ Sign of Δ_{atm} fixed

G.L. Fogli, E. Lisi, hep-ph/9604415



Two more ambiguities:

- ▷ the octant clones
- ▷ the sign clones

Of other clones

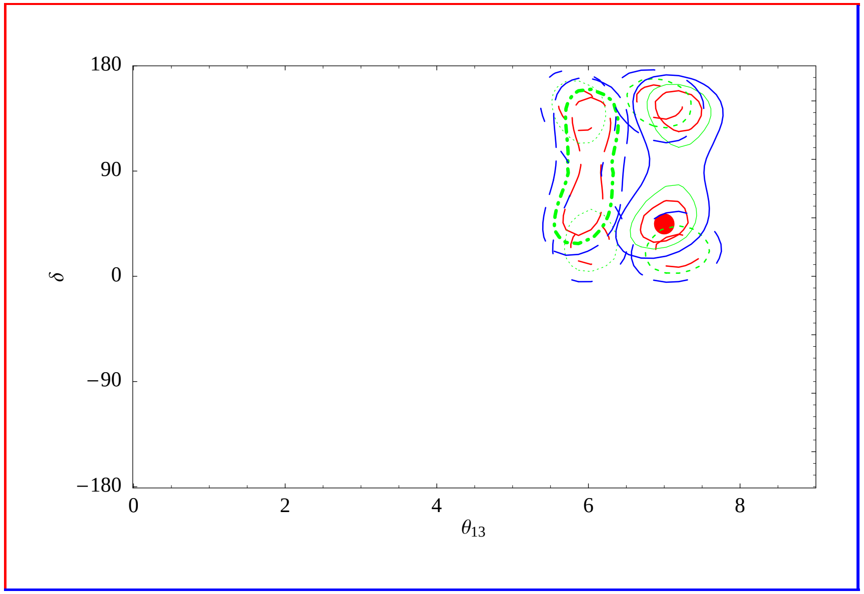
As a fourth step:

- ▷ $\theta_{23} \neq 45°$
- ▷ Sign of Δ_{atm} variable

V. Barger *et al.*, hep-ph/0112119

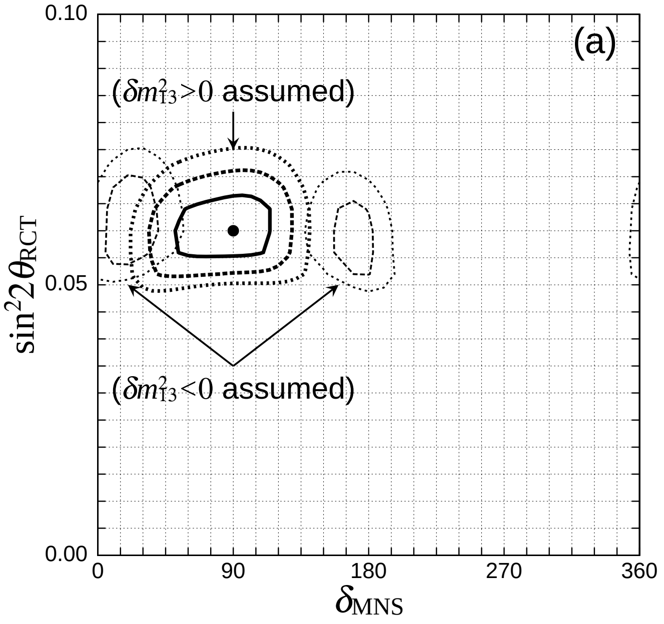
Three more ambiguities:

- ▷ the octant clones
- ▷ the sign clones
- ▷ the mixed clones



The same at T2-HK

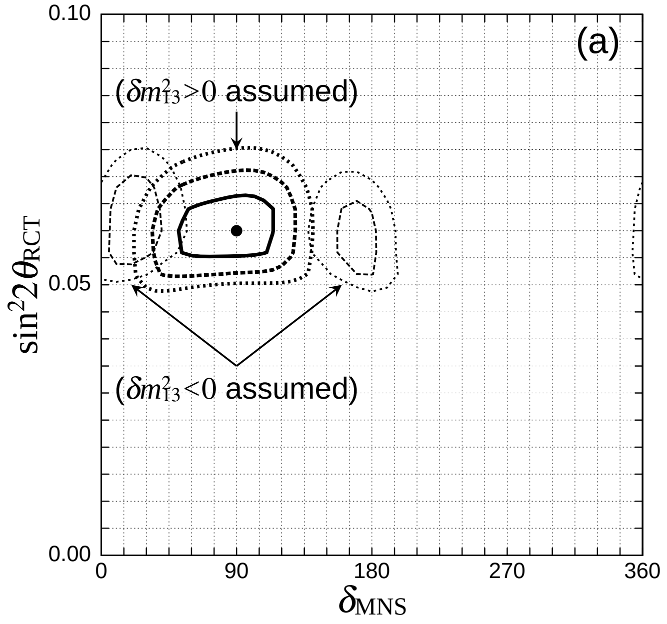
The sign degeneracy



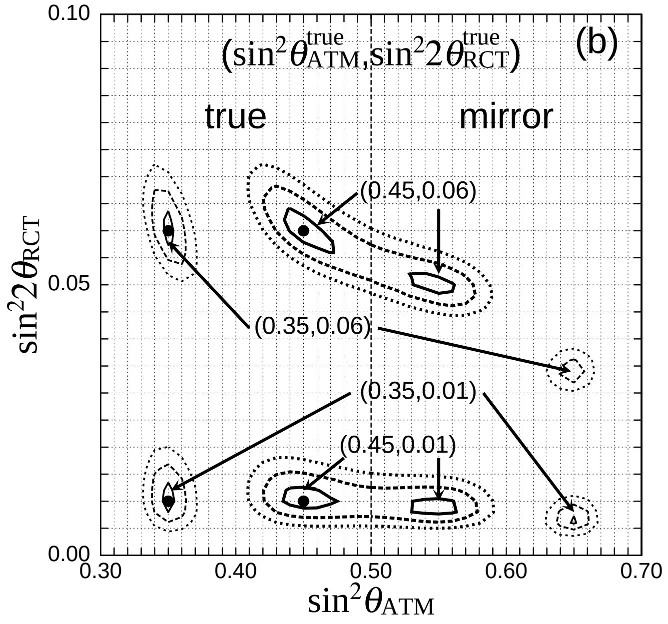
K. Hagiwara, hep-ph/0410229

The same at T2-HK

The sign degeneracy



The octant degeneracy



K. Hagiwara, hep-ph/0410229

Alternatives?

- The Beta Beam
  - very low-γ BB

    C. Volpe, hep-ph/0303222, hep-ph/0403293
  - low-γ BB plus the SPL

    J. Bouchez *et al.*, hep-ph/0310059
  - maximum SPS-γ BB

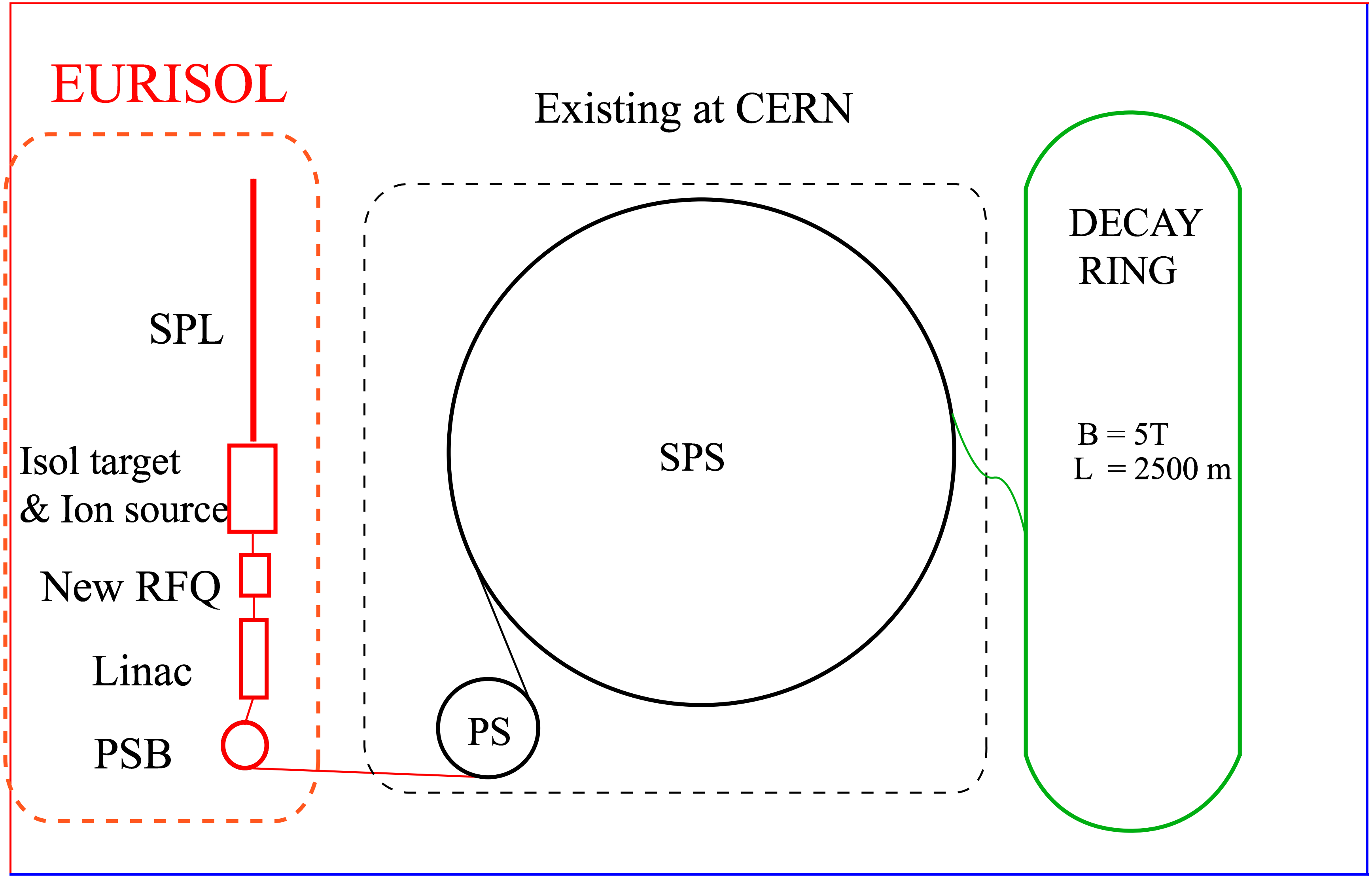
    J. Burguet-Castell *et al.*, hep-ph/0503021
  - medium-γ BB

    J. Burguet-Castell *et al.*, hep-ph/0503021
  - very high-γ BB

    P. Migliozzi and F. Terranova, hep-ph/0405081

I will not cover options (1) and (5).

The Beta-Beam at CERN



The Golden channel: β-beam

$$\boxed{{}^{18}\mathrm{Ne}} \rightarrow \begin{cases} e^{+} \\ {}^{18}\mathrm{F} \\ \boxed{\nu_e \rightarrow \nu_\mu \rightarrow \mu^{-}} \end{cases} \qquad \mathit{Signal}$$

The oscillation probability is

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

The SPL and low-γ Beta Beam

CERN design for 2.2 GeV superbeam
and a low-γ β-beam:
$\gamma = 60$ for ^{6} He;
$\gamma = 100$ for ^{18} Ne

- 440 Kton Water Čerenkov (WC)
  $L = 130$ Km (Frejus)
  UNO Collaboration, hep-ex/0005046;
  D. Casper, Nucl. Phys. Proc. Suppl. 112 (2002) 161.

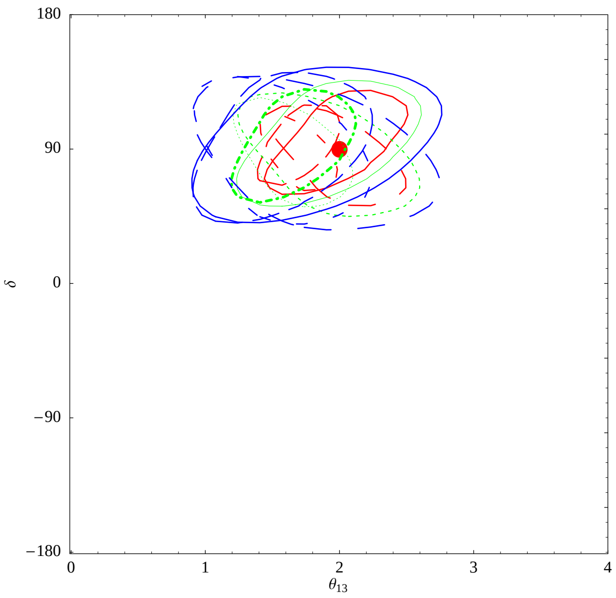
The SPL and low-γ Beta Beam

Consider the $\nu_e \to \nu_\mu$ at the BB:

one massive Water Čerenkov, with baseline $L = 130$

J. Bouchez *et al.*, hep-ph/0310059

- 440 Kton WC-BB

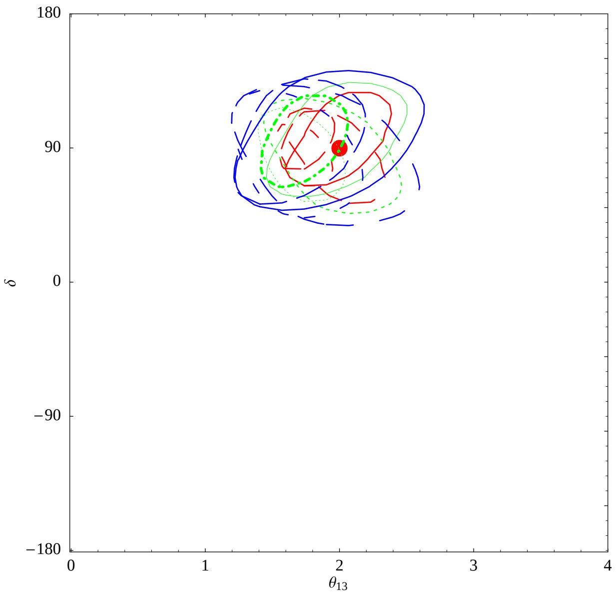


$\bar{\theta}_{13} = 2° \; \bar{\delta} = 90°$

The SPL and low-γ Beta Beam

You can now add $\nu_\mu \to \nu_e$ at the SPL:
same detector, same baseline

- 440 Kton WC-BB
- 440 Kton WC-SPL

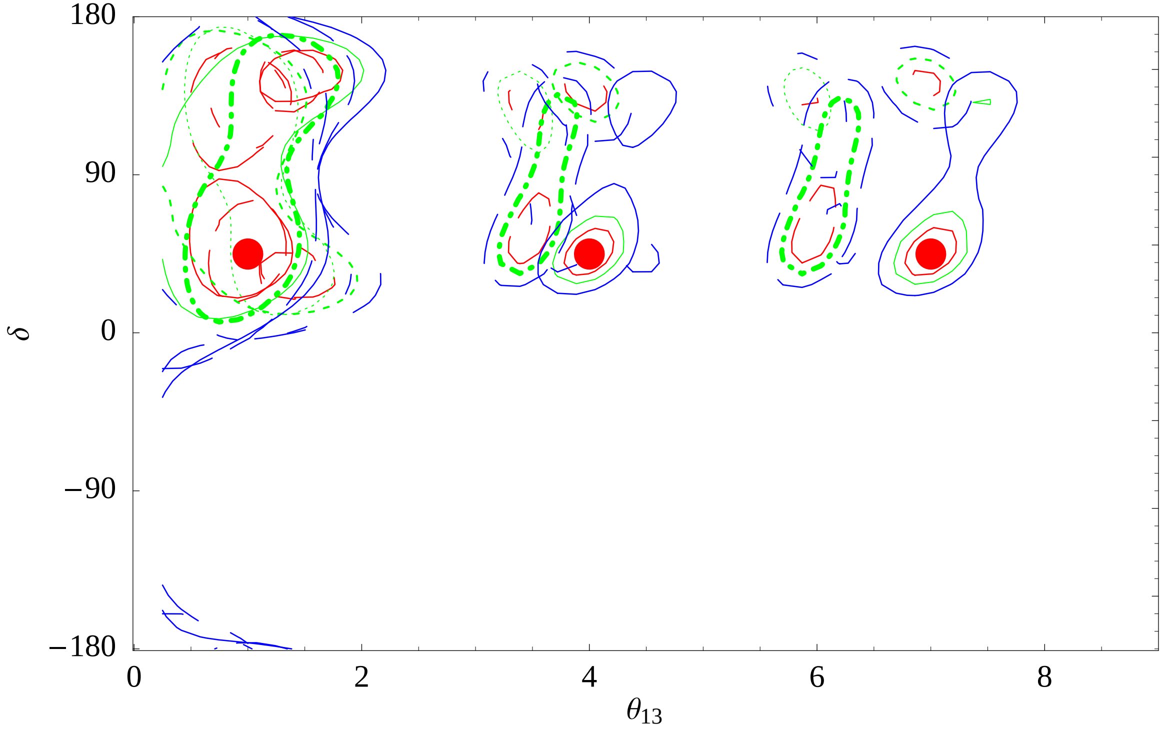


$\bar{\theta}_{13} = 2^\circ \; \bar{\delta} = 90^\circ$

The SPL and low-γ Beta Beam

This is the general situation for $\delta \neq 90°$.

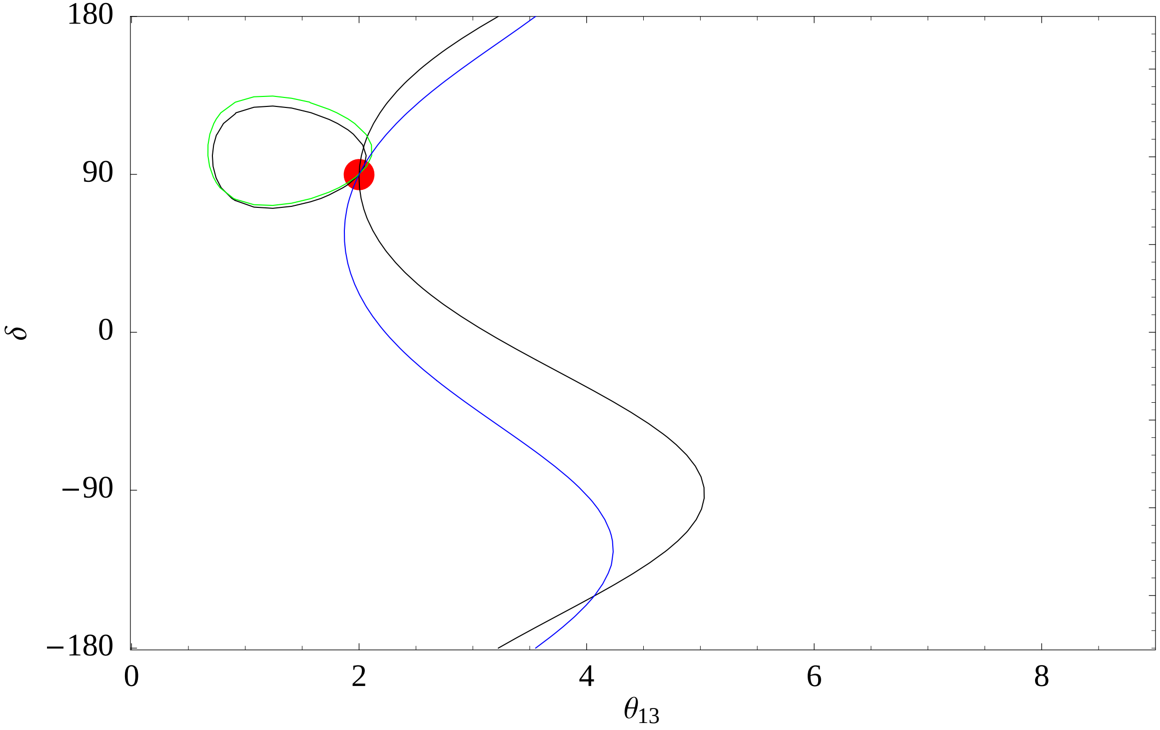
A. Donini *et al.*, hep-ph/0406132



$$\bar{\theta}_{13} = 1°, 4°, 7° \quad \bar{\delta} = 45°$$

The SPL and low-γ Beta Beam

Unfortunately, there is NO SYNERGY:
same detector, same baseline, SAME ENERGY!



$$\bar{\theta}_{13} = 2^\circ \ \bar{\delta} = 90^\circ$$

The maxSPS-γ Beta Beam

The maximum γ at the SPS is:

$\gamma_{^6He} = \gamma_{^{18}Ne} = 150$

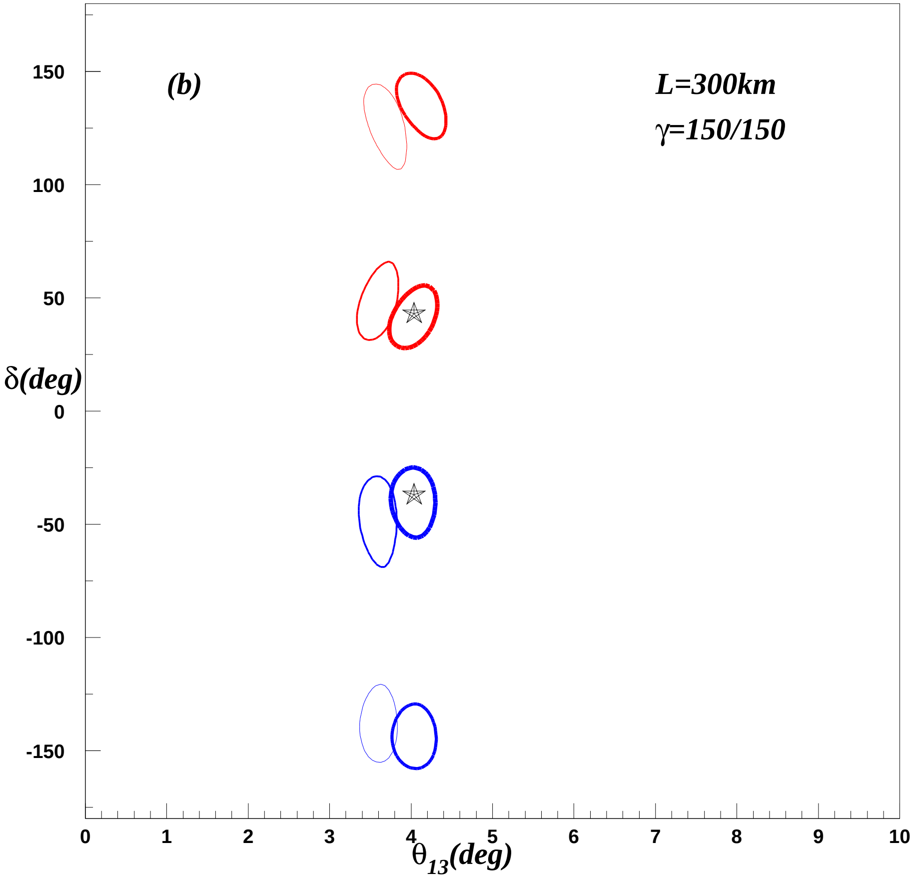
The same detector:

- 440 Kton Water Čerenkov (WC)
  $L = 300$ Km (Canfran?)
  UNO Collaboration, hep-ex/0005046;
  D. Casper, Nucl. Phys. Proc. Suppl. 112 (2002) 161.

In this case, energy resolution can be used

J. Burguet-Castell *et al.*, hep-ph/0503021

The maxSPS-γ Beta Beam



$\bar{\theta}_{13} = 4^\circ$ and $\bar{\delta} = 40^\circ, -40^\circ$

J. Burguet-Castell *et al.*, hep-ph/0503021

The medium-γ Beta Beam

Using an upgraded SPS or the LHC, we could increase the energy:

$\gamma_{^6He} = \gamma_{^{18}Ne} = 350$

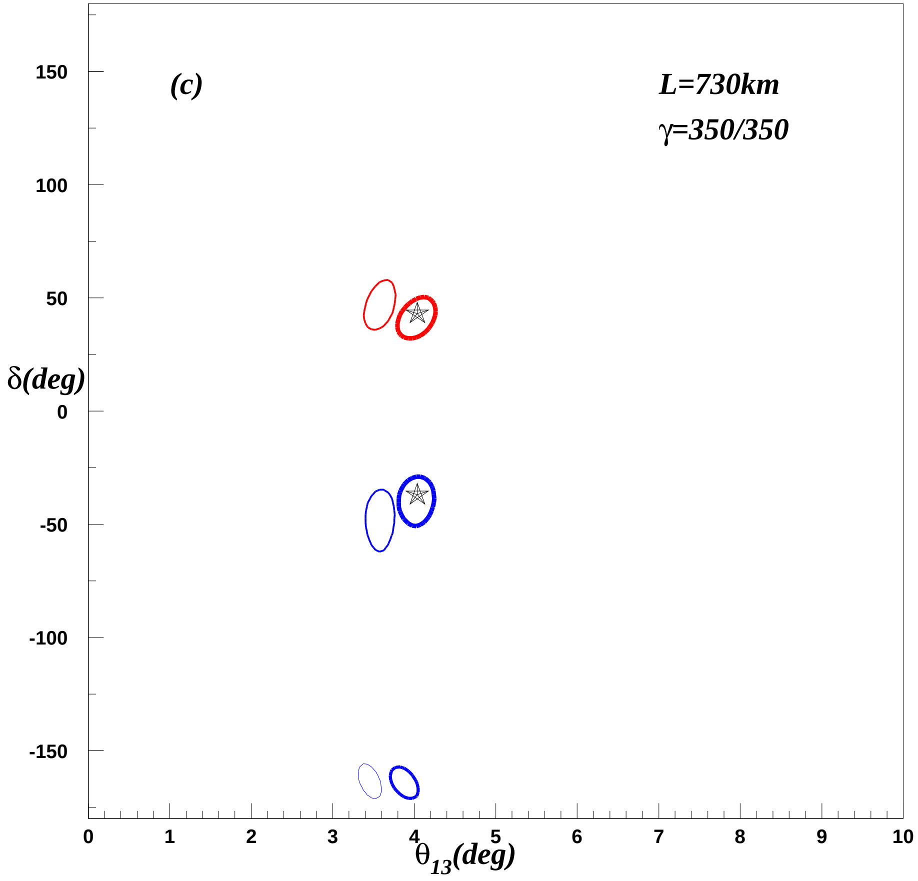
The same detector:

- 440 Kton Water Čerenkov (WC)
  $L = 732$ Km (Gran Sasso or Soudan)
  UNO Collaboration, hep-ex/0005046;
  D. Casper, Nucl. Phys. Proc. Suppl. 112 (2002) 161.

In this case, energy resolution can be used

J. Burguet-Castell *et al.*, hep-ph/0503021

The medium-γ Beta Beam



$\bar{\theta}_{13} = 4^\circ$ and $\bar{\delta} = 40^\circ, -40^\circ$

J. Burguet-Castell *et al.*, hep-ph/0503021

The Ultimate Facility

First hypothesis:

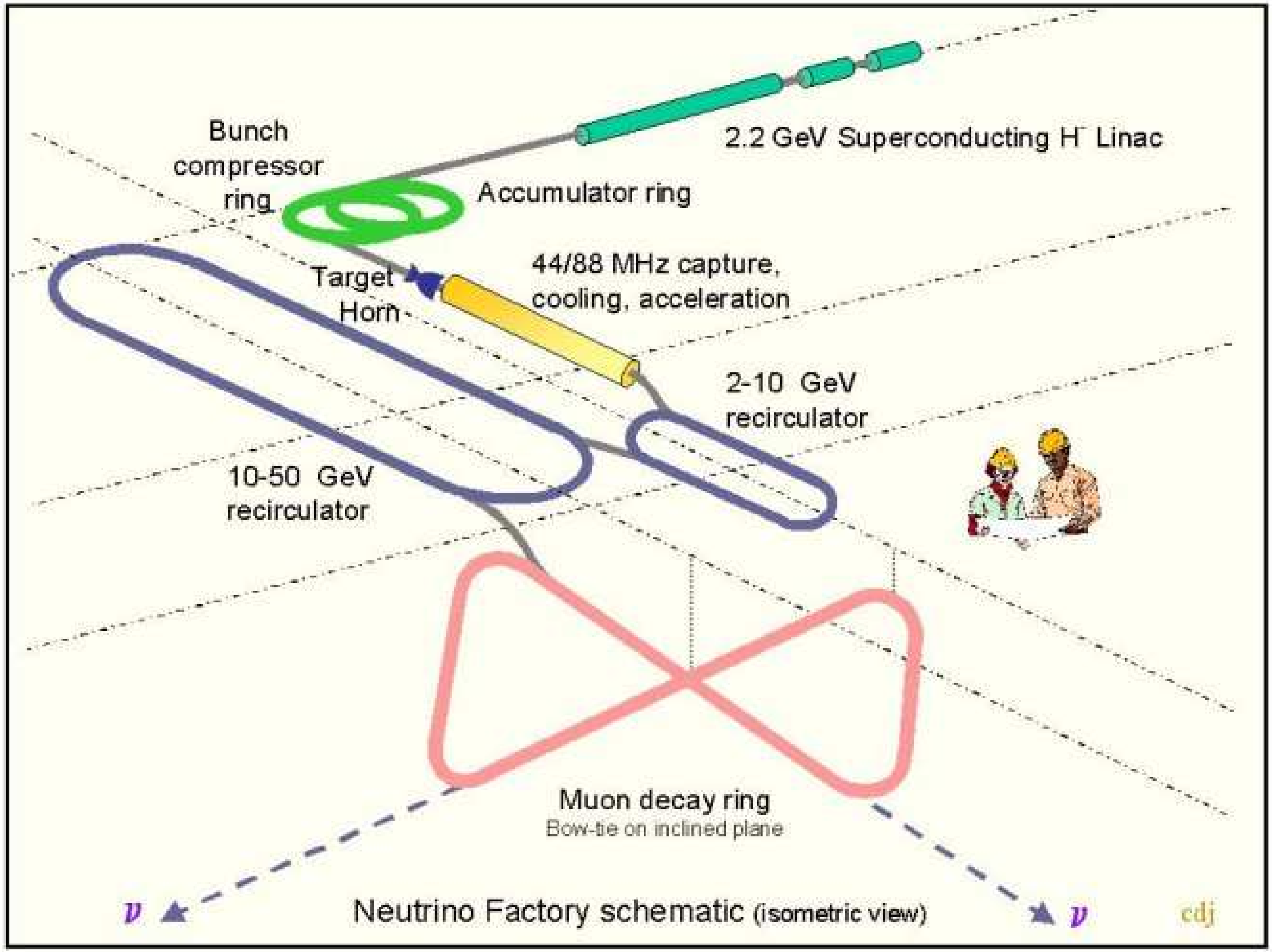
- ▷ Neutrino Factory → Magnetized Iron Detector
- ▷ Neutrino Factory → Emulsion Cloud Chamber
- ▷ SuperBeam → Water Čerenkov

Second hypothesis:

- ▷ Neutrino Factory → Magnetized Iron Detector
  - Golden Channel $\nu_e \rightarrow \nu_\mu$
  - Disappearance $\nu_\mu \rightarrow \nu_\mu$
- ▷ Neutrino Factory → Emulsion Cloud Chamber

Caveat: Magnetized Iron Detector simulation must be updated

The Neutrino Factory at CERN



The Golden channel: ν-factory

A. Cervera *et al.*, hep-ph/0002108

$$\boxed{\mu^+} \rightarrow \begin{cases} e^+ & \\ \boxed{\bar{\nu}_\mu \rightarrow \mu^+} & \mathit{Background} \\ \boxed{\nu_e \rightarrow \nu_\mu \rightarrow \mu^-} & \mathit{Signal} \end{cases}$$

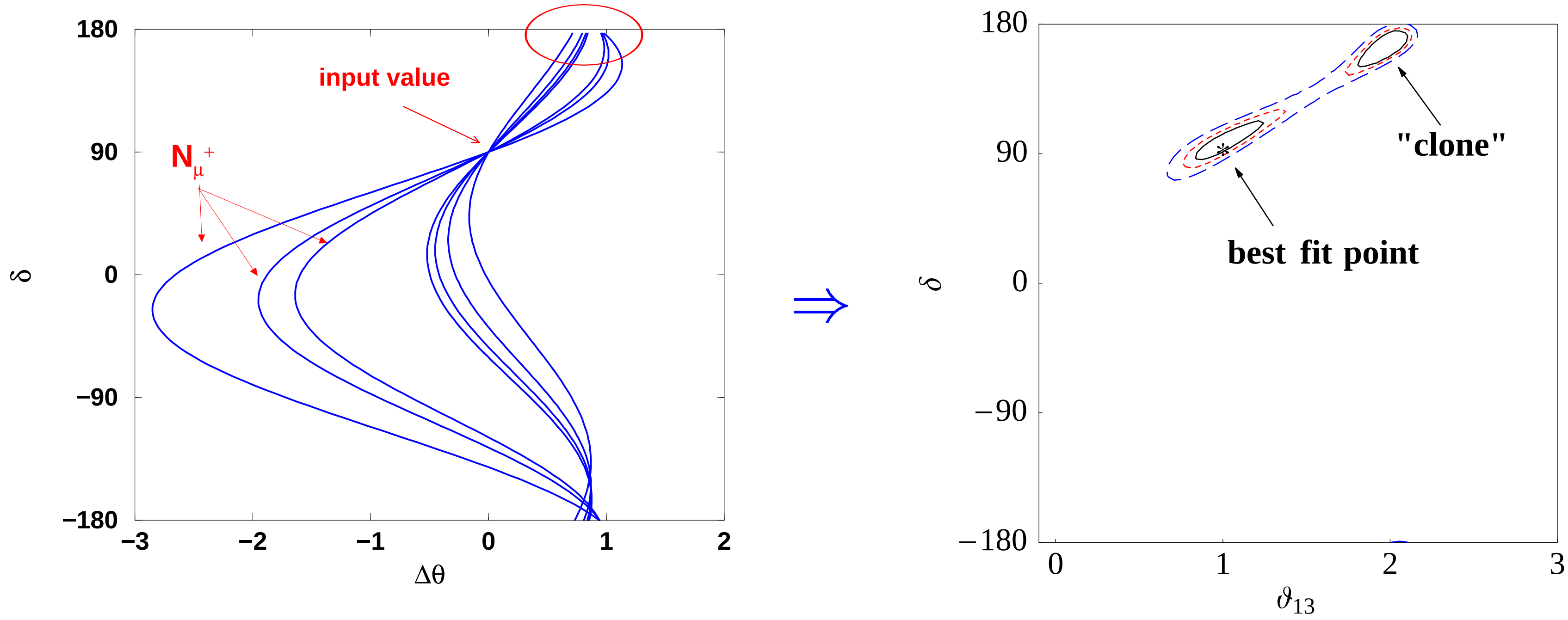
The oscillation probability is

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

Golden muons at $L = 2810$ Km

Ten years of data taking: two polarities

(μ^+ and μ^- in the storage ring)



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

The Silver channel: ν-factory

A. Donini, D. Meloni and P. Migliozzi, hep-ph/0206034

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

The oscillation probability is

$$P^{\pm}_{e\tau} = X^{\tau}_{\pm} \sin^2(2\,\theta_{13})$$

$$-Y^{\tau}_{\pm} \cos\left(\delta \mp \frac{\Delta_{atm} L}{2}\right) \cos\theta_{13} \sin(2\,\theta_{13})$$

$$+Z^{\tau} + \dots$$

The Coefficients

For the golden channel we have:

$$\begin{cases} X_{\pm} & = & \Delta^2_{atm} \times f^{\pm}_X\,(\theta_{23}, A, L, E_\nu) \\ Y_{\pm} & = & \Delta_{sol} \times \Delta_{atm} \times f^{\pm}_Y\,(\theta_{12}, \theta_{23}, A, L, E_\nu) \\ Z & = & \Delta^2_{sol} \times f_Z\,(\theta_{12}, \theta_{23}, A, L, E_\nu) \end{cases}$$

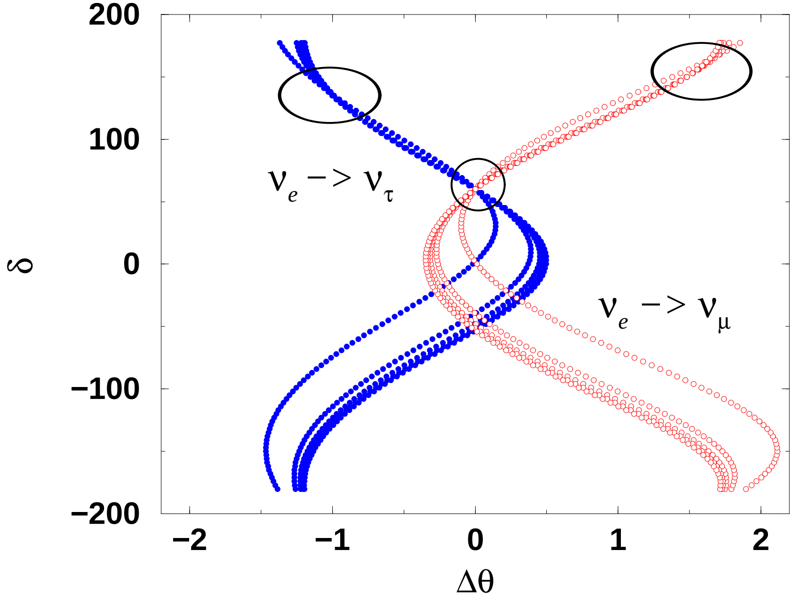
For the silver channel we have:

$$\begin{cases} X^{\tau}_{\pm} & = & (c^2_{23}/s^2_{23}) X_{\pm} \\ Y^{\tau}_{\pm} & = & Y_{\pm} \\ Z^{\tau} & = & (s^2_{23}/c^2_{23}) Z \end{cases}$$

($+$ neutrinos, $-$ antineutrinos)
Notice: X, Z interchange $\theta_{23} \to \pi/2 - \theta_{23}$.

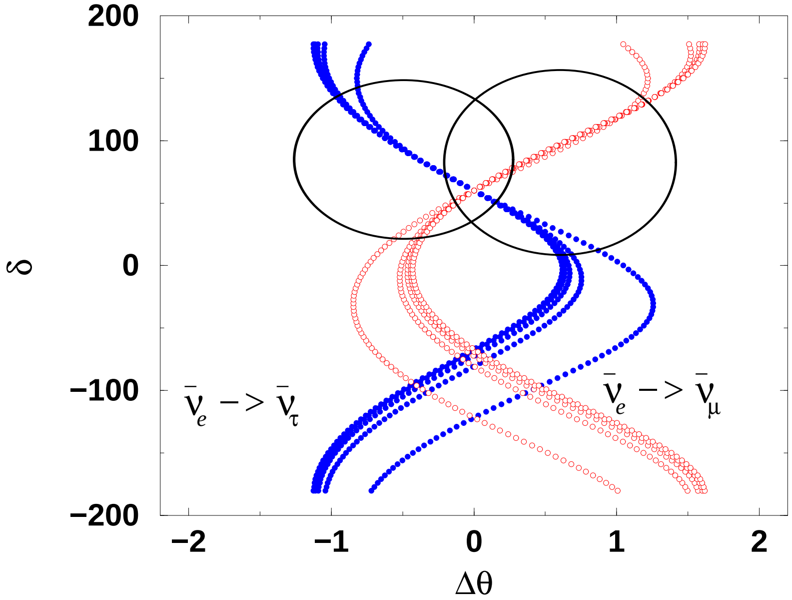
The intrinsic clones

$L = 732$ Km



Neutrinos

$L = 732$ Km



Antineutrinos

$$\begin{cases} \bar{\theta}_{13} & = & 5^\circ \\ \bar{\delta} & = & 90^\circ \end{cases}$$

$$\Delta\theta = \theta_{13} - \bar{\theta}_{13}$$

The ν-factory/detectors setup I

CERN design for a 2.2 GeV superbeam
and a 50 GeV Neutrino Factory

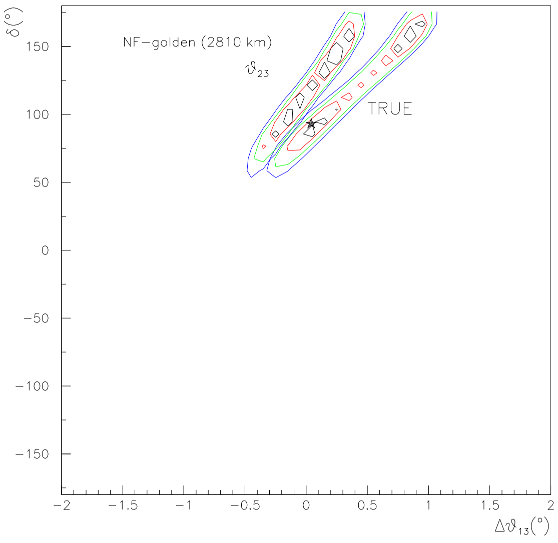
- NF: 40 Kton Magnetized iron detector (MID)
  $L = 2810$ Km (Canary Islands)
  A. Cervera *et al.*,
  Nucl. Instr. Meth. A 451 (2000) 123; NuFact99, Lyon
- NF: 4 Kton Emulsion Cloud Chamber (ECC)
  $L = 732$ Km (Gran Sasso) or $L = 2810$ Km
  D. Autiero *et al.*, hep-ph/0305185; NuFact03, New York
- SB: 400 Kton Water Čerenkov (WC)
  $L = 130$ Km (Frejus)
  A. Blondel *et al.*,
  Nucl. Instr. Meth. A 503 (2001) 173; NuFact01, Tsukuba

One detector

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

A. Cervera *et al.*, hep-ph/0002108

- 40 Kton MID



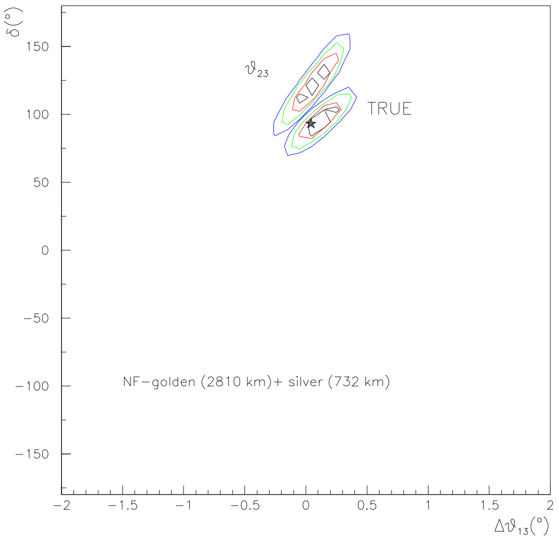
$$\bar{\theta}_{13} = 2^\circ \; \bar{\delta} = 90^\circ$$

Two detectors

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

A. Donini *et al.*, hep-ph/0206034

- 40 Kton MID
- 4 Kton ECC



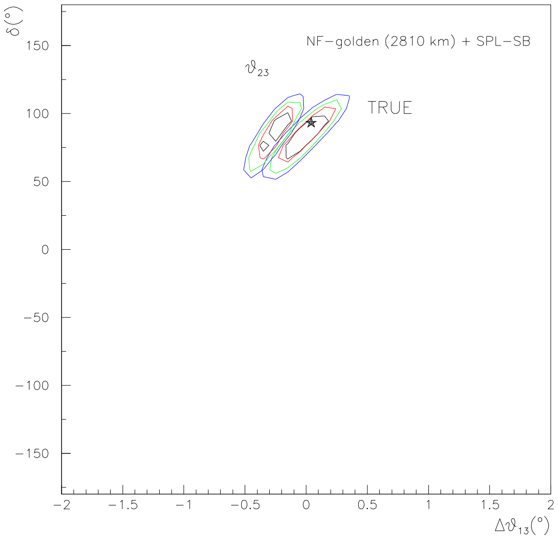
$$\bar{\theta}_{13} = 2° \; \bar{\delta} = 90°$$

Two detectors

... or of the Superbeam-driven Water Čerenkov.

J. Burguet-Castell *et al.*, hep-ph/0207080

- 40 Kton MID
- 400 Kton WC



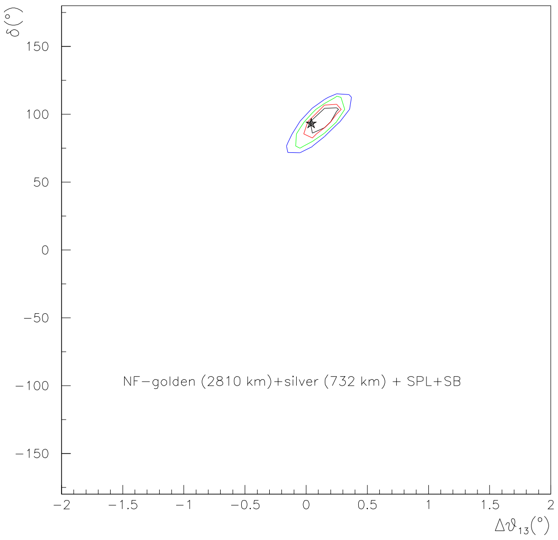
$$\bar{\theta}_{13} = 2^\circ \ \bar{\delta} = 90^\circ$$

The Three Detectors

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

A. Donini, hep-ph/0310014

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



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

The ν-factory/detectors setup II

CERN design for a 2.2 GeV superbeam
and a 50 GeV Neutrino Factory

- NF: 40 Kton Magnetized iron detector (MID)
  $L = 2810$ Km (Canary Islands)

  A. Cervera *et al.*,
  Nucl. Instr. Meth. A 451 (2000) 123; NuFact99, Lyon
- NF: 4 Kton Emulsion Cloud Chamber (ECC)
  $L = 732$ Km (Gran Sasso) or $L = 2810$ Km
  D. Autiero *et al.*, hep-ph/0305185; NuFact03, New York

This is very preliminary: different options are considered in the disappearance channel.

Preliminar analysis at the NuFactory

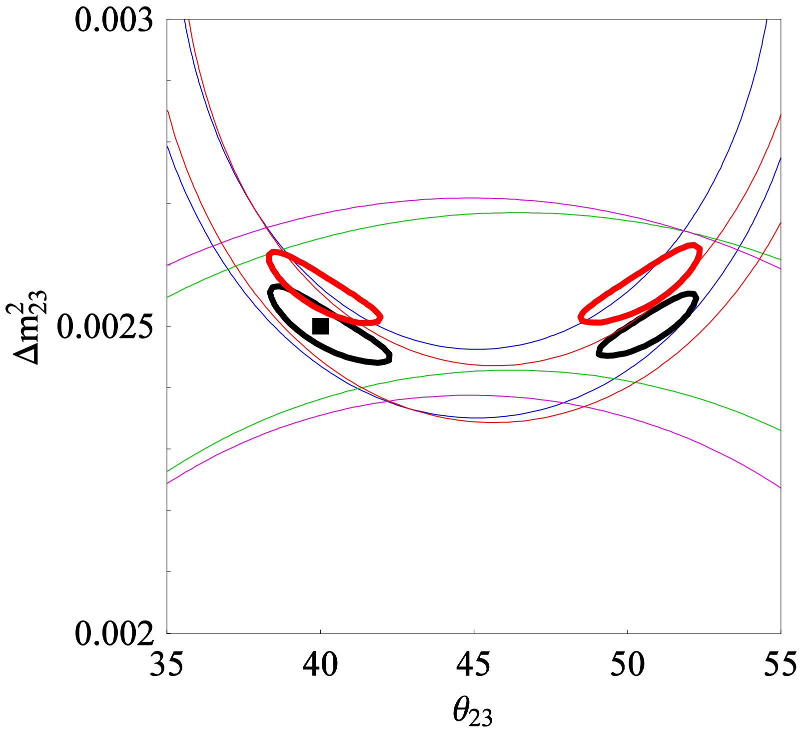
5yr ν_μ + 5yr $\bar{\nu}_\mu$ exposure with a 40Kt iron calorimeter for the NF

- Possible Setups:
    - L = 3000Km E = 20, 50 GeV
    - L = 7000Km E = 50 GeV
- 5 GeV bins considered
- Efficiency:
    - ε_μ = 0.5 for neutrinos
    - ε_μ = 0.33 for antineutrinos
- Systematics = 2%

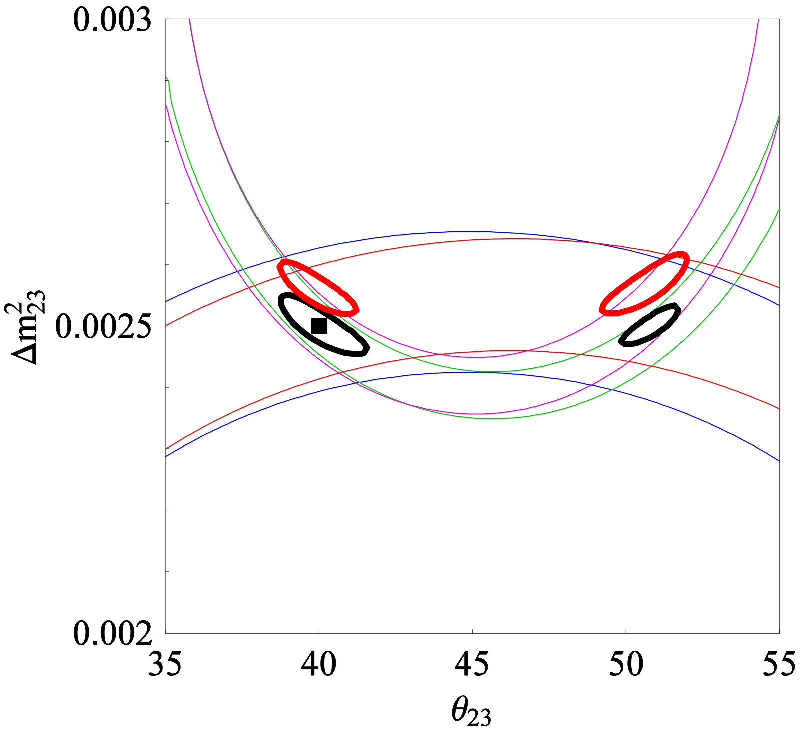
Cervera *et al.* hep-ph/0002108

See Bueno *et al.* hep-ph/0005007 for an Icarus analysis

Neutrino Factory



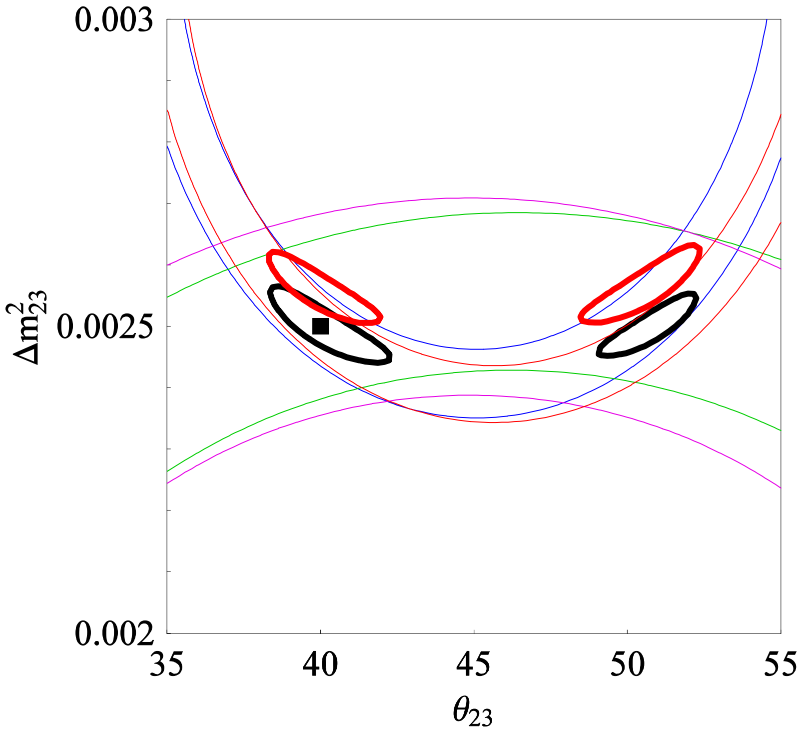
E = 50 GeV
L = 3000 Km



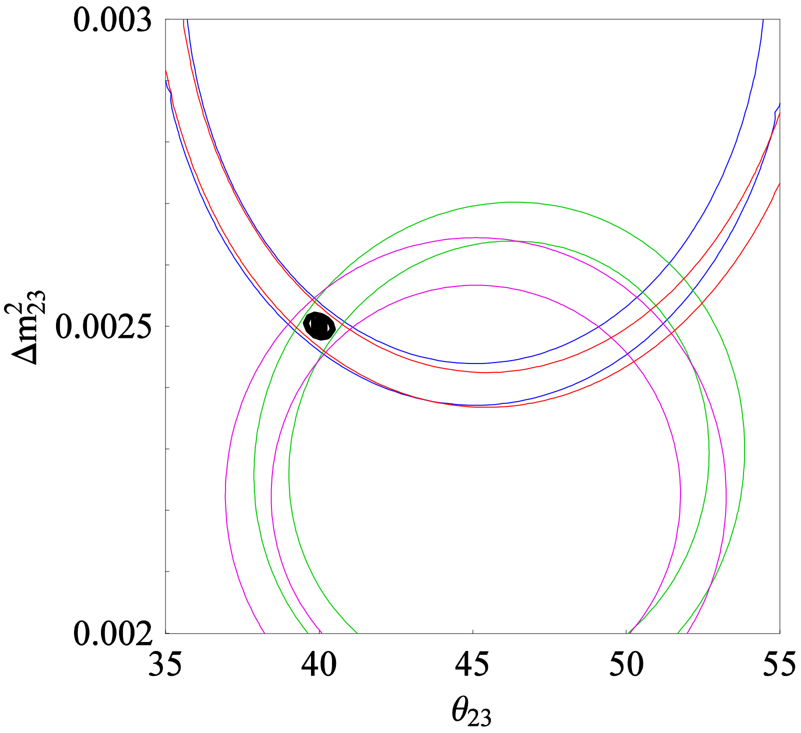
E = 20 GeV
L = 3000 Km

Input: $\theta_{23} = 40^o$, $\theta_{13} = 6^o$, $\delta = 0^o$

Neutrino Factory



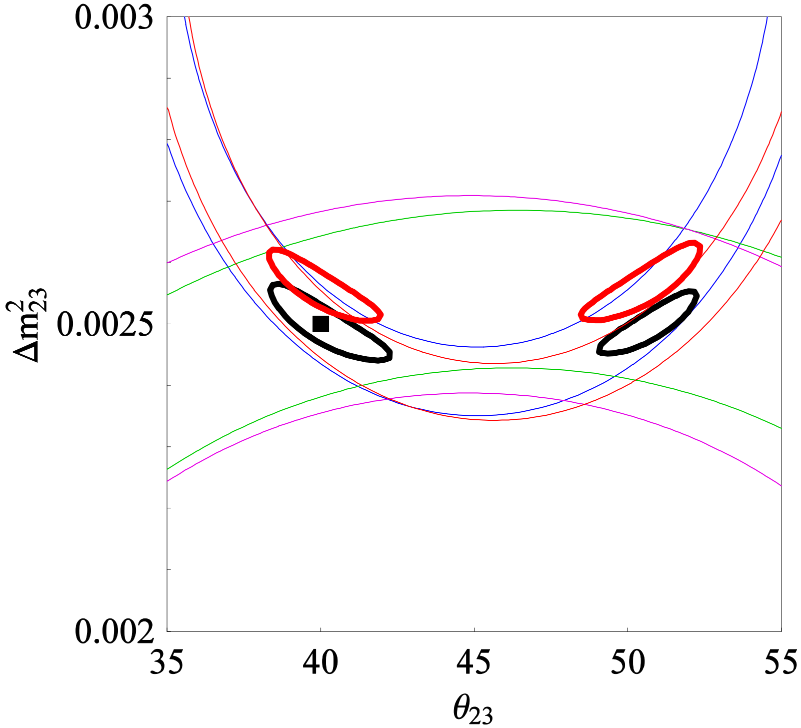
E = 50 GeV
L = 3000 Km



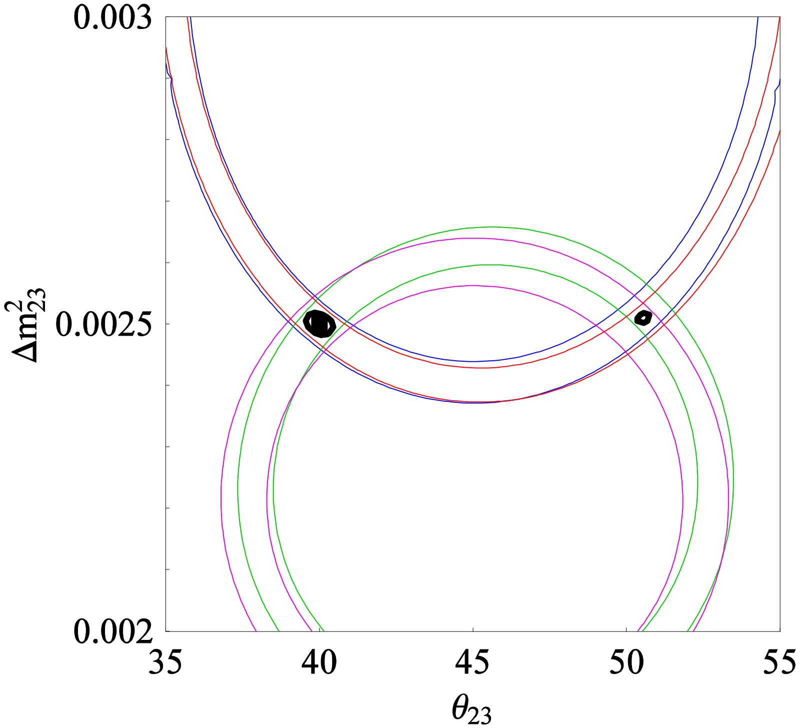
E = 50 GeV
L = 7000 Km

Input: $\theta_{23} = 40^o$, $\theta_{13} = 6^o$, $\delta = 0^o$

Neutrino Factory



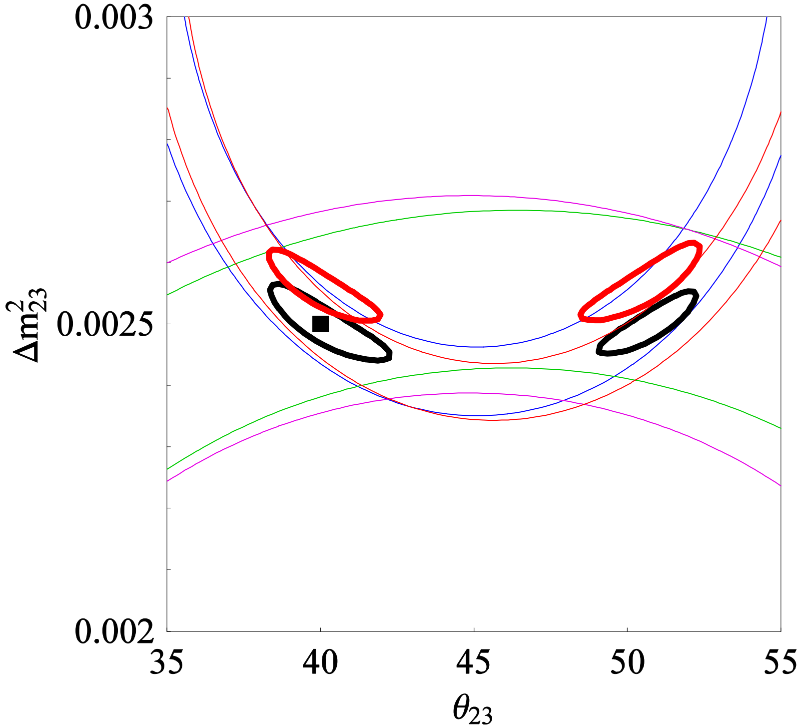
E = 50 GeV
L = 3000 Km



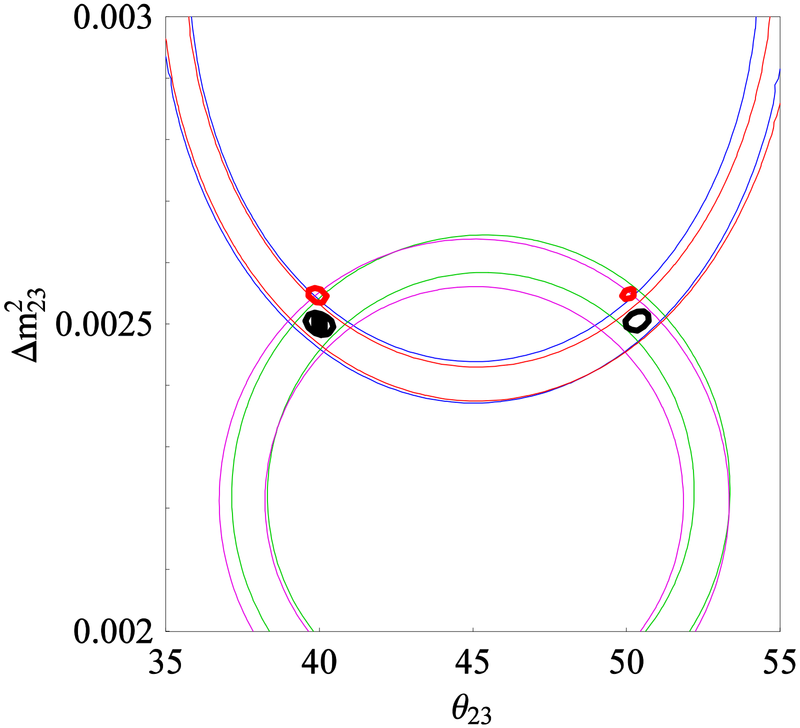
E = 50 GeV
L = 7000 Km

Input: $\theta_{23} = 40^o$, $\theta_{13} = 4^o$, $\delta = 0^o$

Neutrino Factory



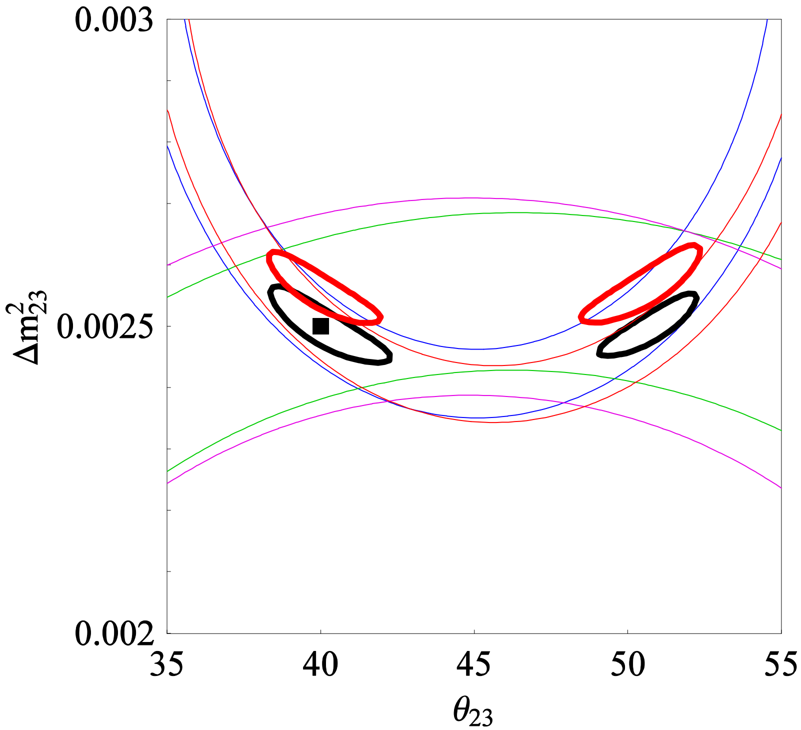
E = 50 GeV
L = 3000 Km



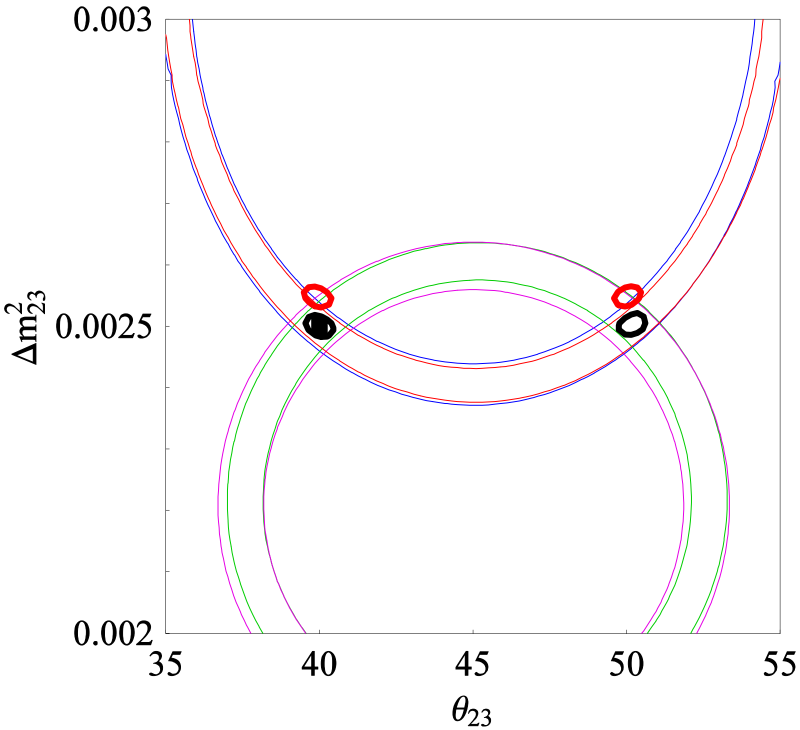
E = 50 GeV
L = 7000 Km

Input: $\theta_{23} = 40^o$, $\theta_{13} = 3^o$, $\delta = 0^o$

Neutrino Factory



E = 50 GeV
L = 3000 Km



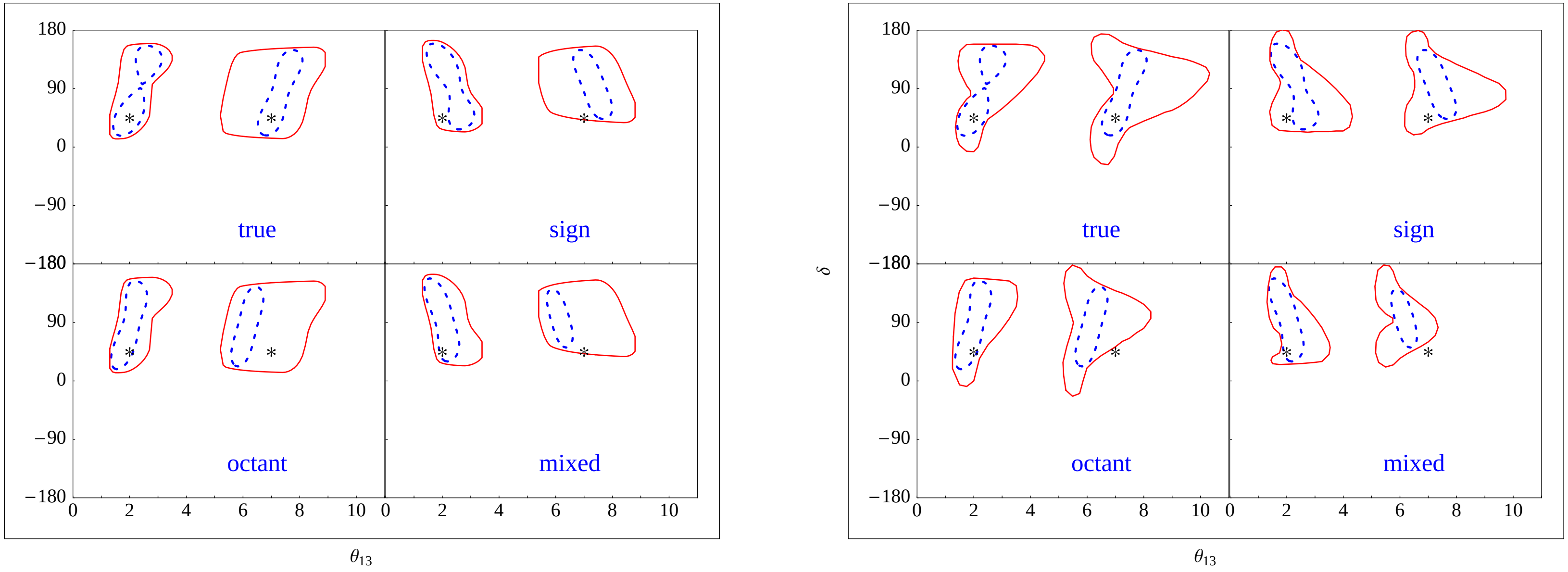
E = 50 GeV
L = 7000 Km

Input: $\theta_{23} = 40^\circ$, $\theta_{13} = 2^\circ$, $\delta = 0^\circ$

Atmospheric uncertainties, I

Taking into account present uncertainties on the atmospheric parameters $\theta_{23}, \Delta m^2_{atm}$ makes things more difficult:

1) The low-γ Beta Beam with present errors on $\theta_{23}, \Delta m^2_{atm}$

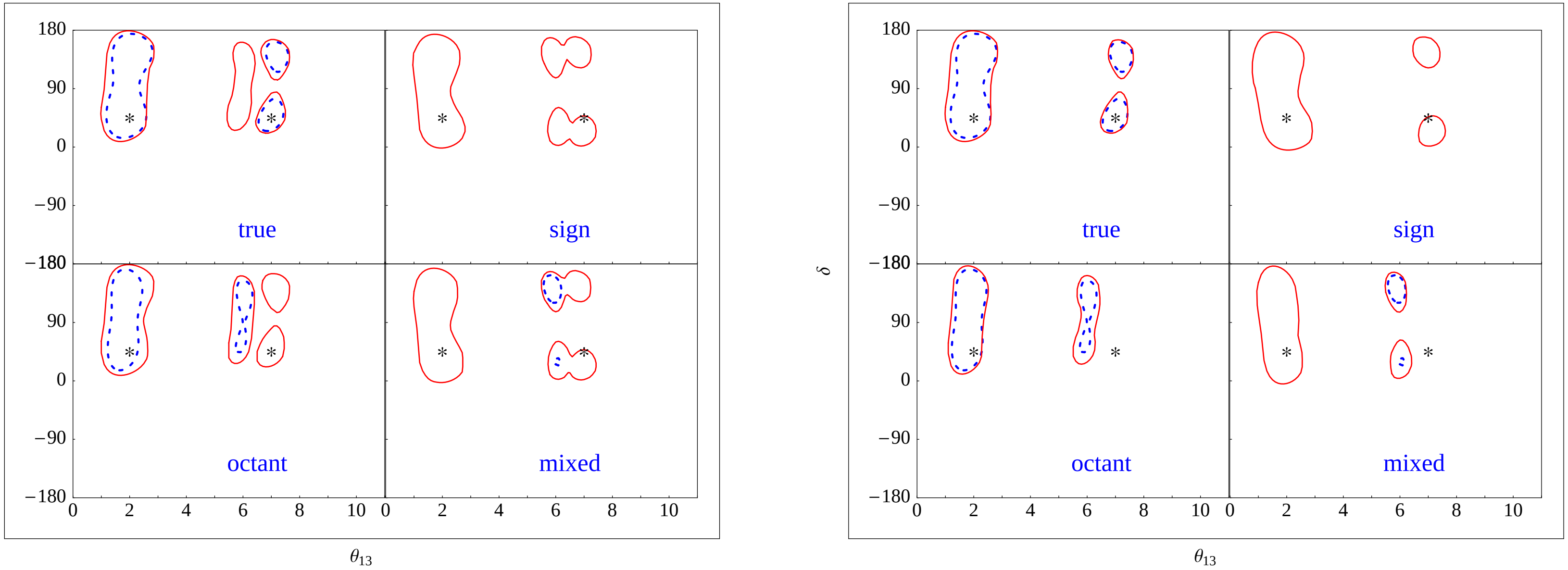


Input parameters: $\bar{\theta}_{13} = 2°, 7°; \bar{\delta} = 45°$

Atmospheric uncertainties, II

Taking into account present uncertainties on the atmospheric parameters $\theta_{23}, \Delta m^2_{atm}$ makes things more difficult:

2) The SPL Super Beam with improved errors on $\theta_{23}, \Delta m^2_{atm}$

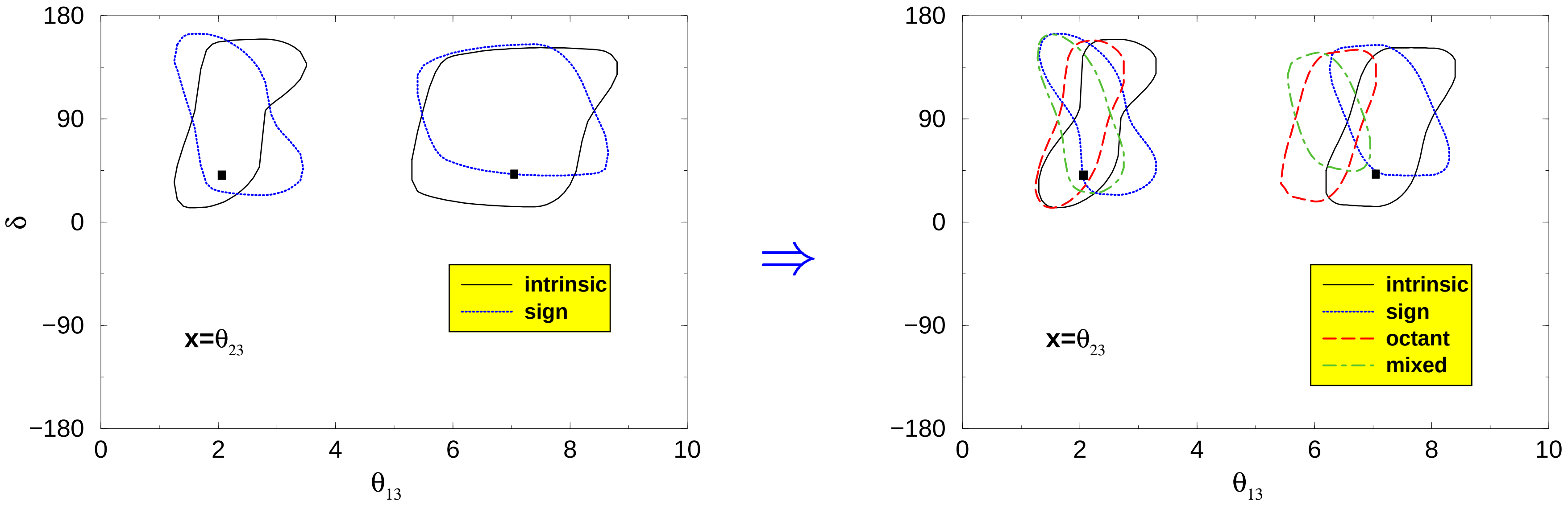


Input parameters: $\bar{\theta}_{13} = 2°, 7°; \bar{\delta} = 45°$

Atmospheric uncertainties, III

Improvement on the errors from other experiments ameliorate the situation:

3) The low-γ Beta Beam after T2K-I; θ_{23} fit

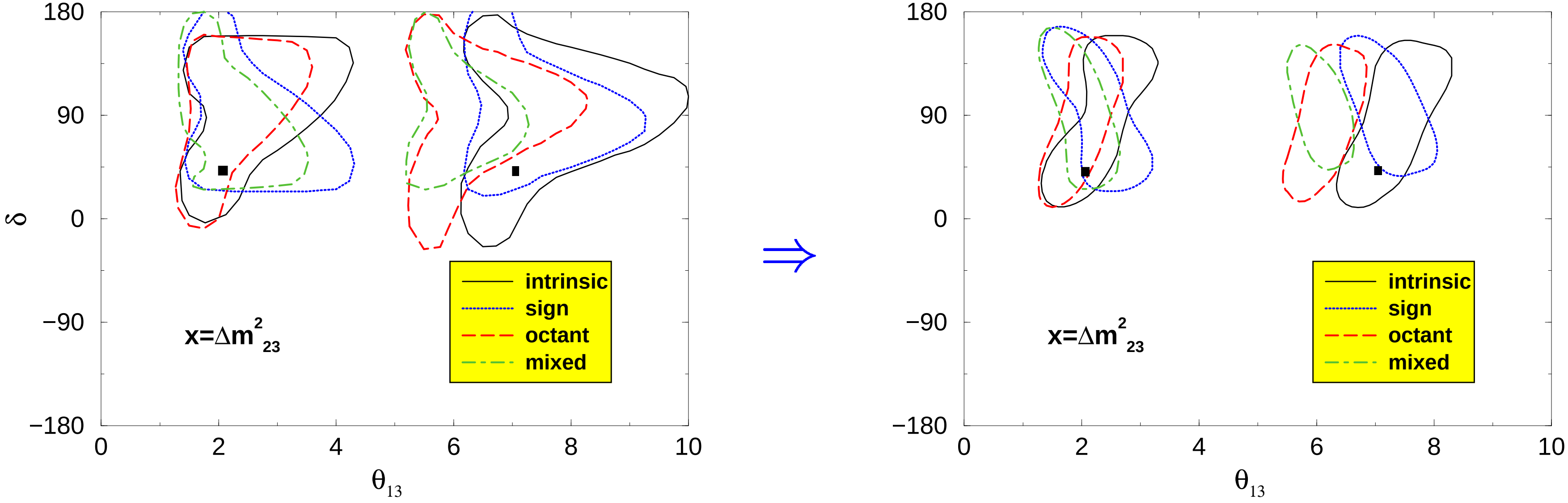


Input parameters: $\bar{\theta}_{13} = 2°, 7°; \bar{\delta} = 45°$

Atmospheric uncertainties, IV

Improvement on the errors from other experiments ameliorate the situation:

4) The low-γ Beta Beam after T2K-I; Δm^2_{atm} fit



Input parameters: $\bar{\theta}_{13} = 2°, 7°; \bar{\delta} = 45°$

Summary of Lecture II

The goal for the future LBL experiments:
measuring $\theta_{13}, \delta, s_{atm}, s_{oct}$

First problem: severe correlations between the parameters

Second problem: huge parametric degeneracies

An experimental prejudice: put every experiment ON PEAK (that is, increase the statistics)

The result of several years theoretical analysis:
if every single experiment is on peak, it is impossible to solve the degeneracies.

Summary of Lecture II

Therefore:

- ▷ Put some experiment ON PEAK (even counting detectors)
- ▷ Put some experiment at different L/E
- ▷ or Build some experiment with BROAD neutrino energy spectrum
- ▷ Look for different channels, either in appearance or disappearance
- ▷ MATTER EFFECTS are useful to solve degeneracies