ν_μ Disappearance at SPL, T2K-I and the NuFactory

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Outline

- Introduction
  - Oscillation parameters
  - Experiments description
- SPL vs T2K-I
- Subleading effects in ν_μ disappearance
  - Δm^2_{atm} and the sign degeneracy
  - θ_{23} and the octant degeneracy
  - The effects of θ_{13} and δ
- T2K-I bounds revised
- The Neutrino Factory
- Conclusions

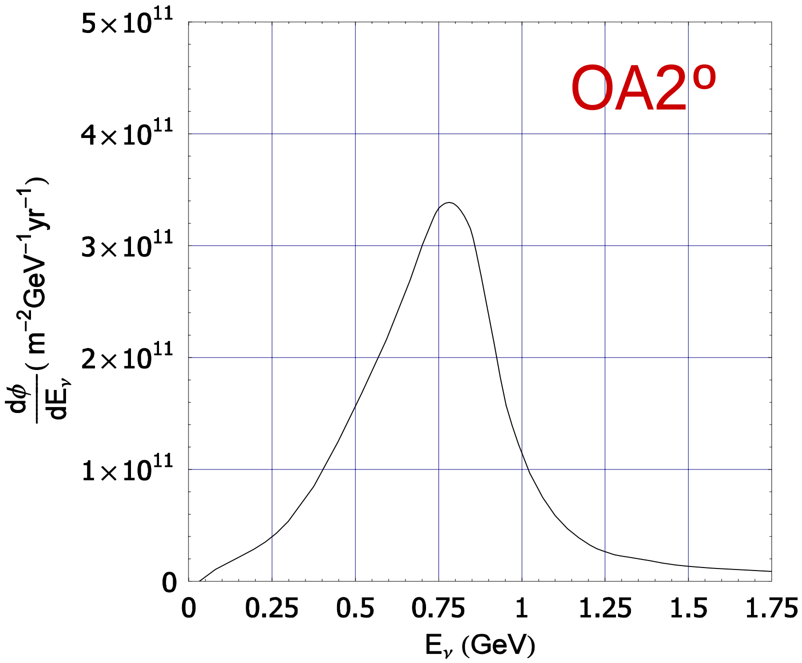
The oscillation parameters

- What we already know (at 3σ)
  - Solar sector $\begin{cases} \Delta m^2_{12} = 8.2^{+1.1}_{-0.9} \cdot 10^{-5} \text{eV}^2 \\ \tan^2 \theta_{12} = 0.39^{+0.21}_{-0.11} \end{cases}$ $\theta_{12} = 28^o–38^o$
  - Atm sector $\begin{cases} \left|\Delta m^2_{23}\right| = 2.2^{+1.4}_{-0.6} \cdot 10^{-3} \text{eV}^2 \\ \tan^2 \theta_{23} = 1^{+1.1}_{-0.5} \end{cases}$ $\theta_{23} = 35^o–55^o$
- What we still do not know
  - $\sin^2 2\theta_{13} < 0.16$ $\theta_{13} < 11.5^o$
  - δ_{cp}
  - Mass hierarchy $s_{atm} = sign\left(\Delta m^2_{23}\right)$
  - Octant of θ_{23} $s_{oct} = sign\left[\tan\left(2\theta_{23}\right)\right]$

M. C. González García hep-ph/0410030

Fluxes

T2K-I

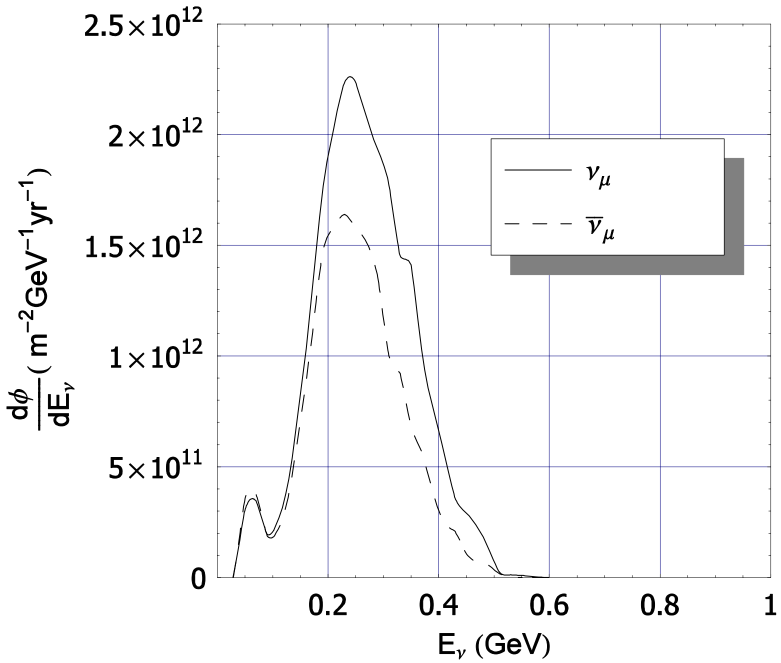


L=295Km

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

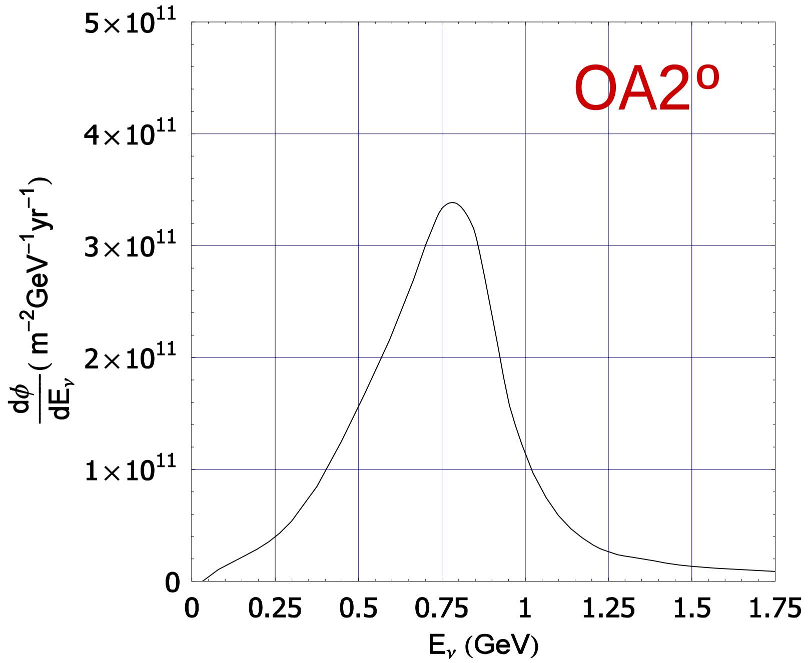
ν_μ flux from π^+ decay $\langle E_\nu \rangle = 0.27 GeV$

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

Old SPL fluxes courtesy of Gilardoni

Fluxes

T2K-I

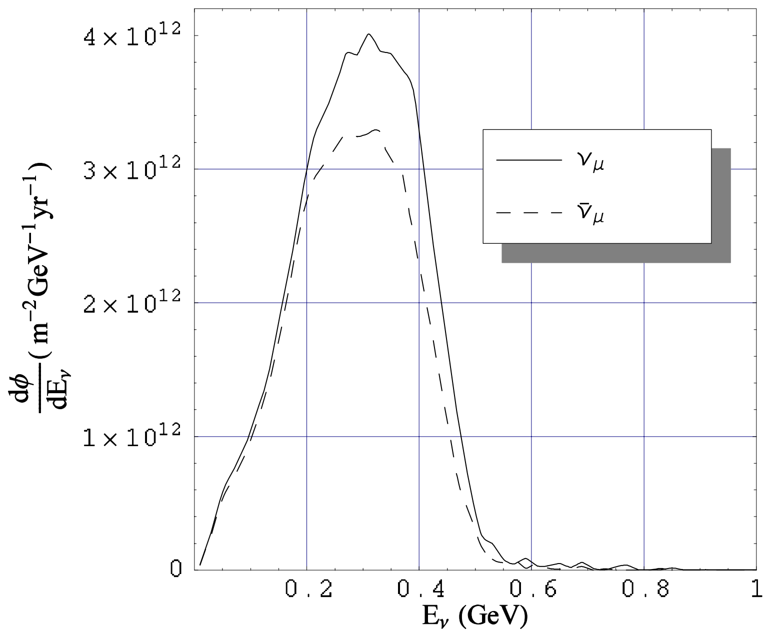


L=295Km

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

$\overline{\nu}_\mu$ 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

Statistics dominated

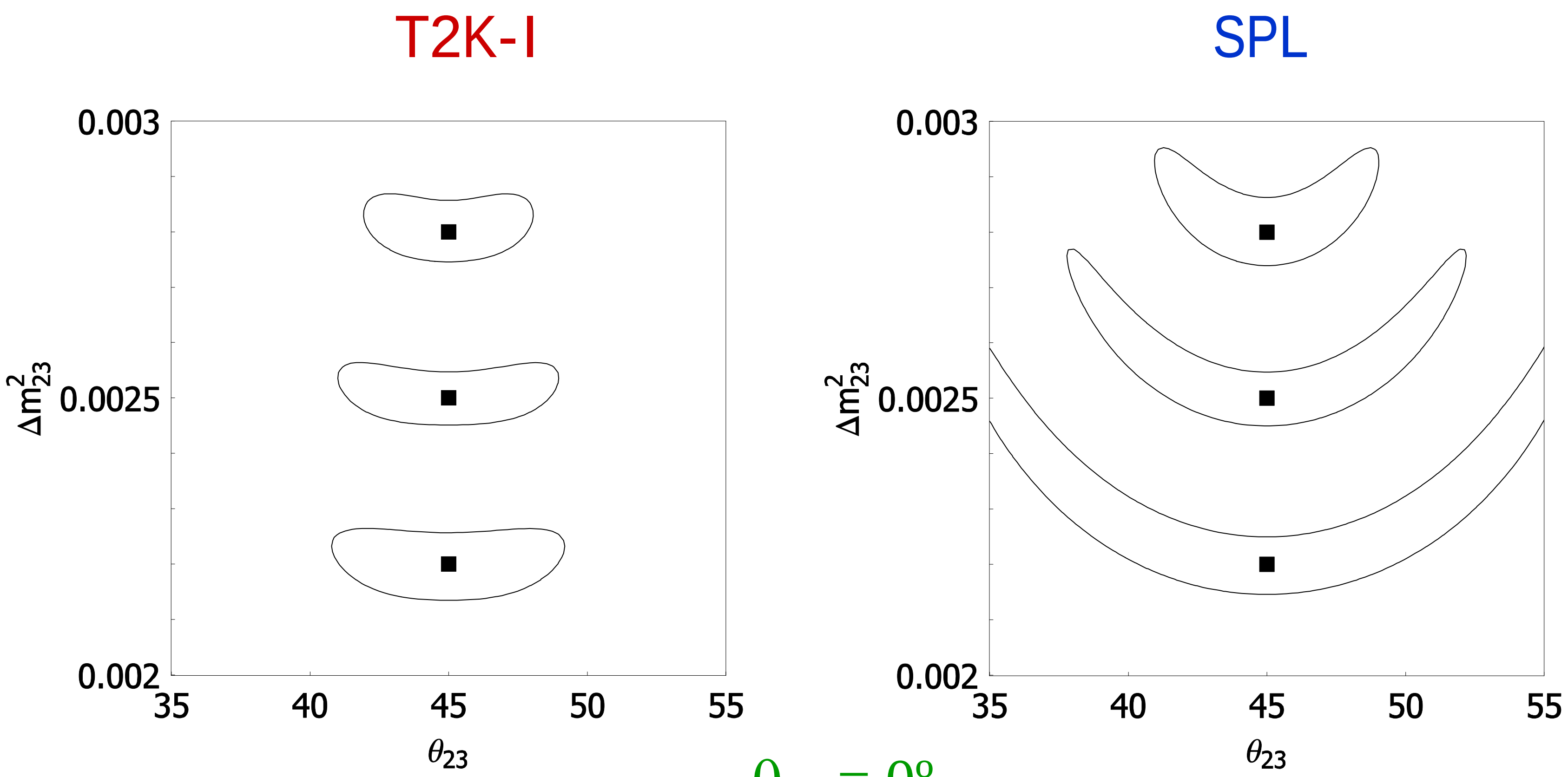
L=130Km

Systematic dominated

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

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

The importance of energy resolution



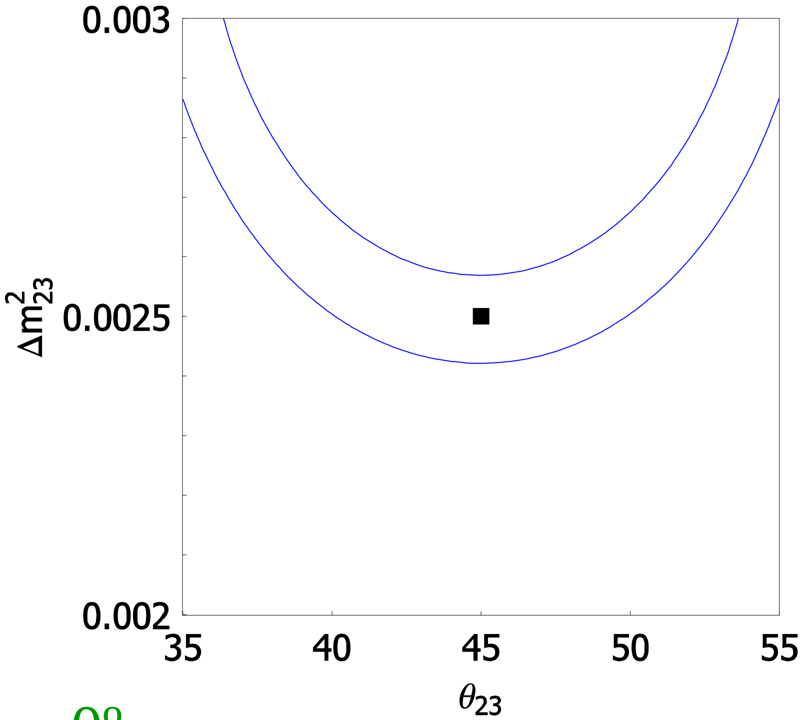
$\theta_{13} = 0^o$
$\delta = 0^o$

90% CL contours, 2 dofs
5% systematic error and backgrounds taken into account

The importance of energy resolution

T2K-I

SPL

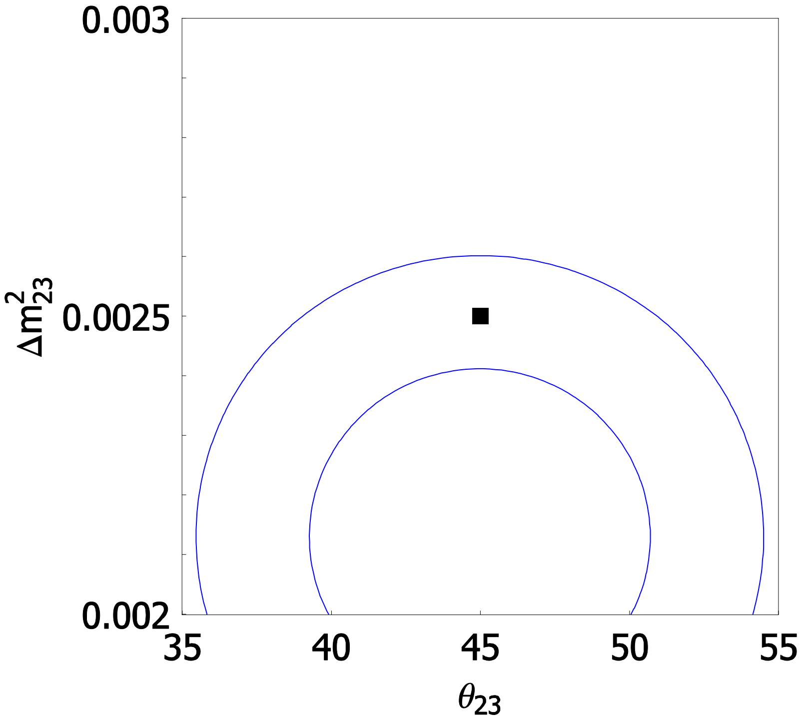


$\theta_{13} = 0^o$
$\delta = 0^o$

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

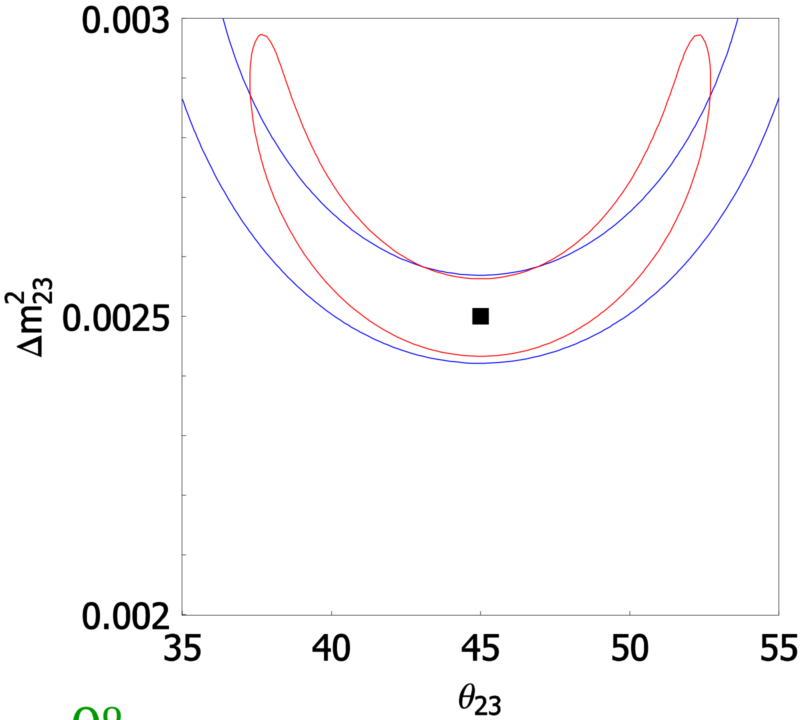
The importance of energy resolution

T2K-I



$E1 = 0.4 - 0.6 GeV$

SPL



$\theta_{13} = 0^o$

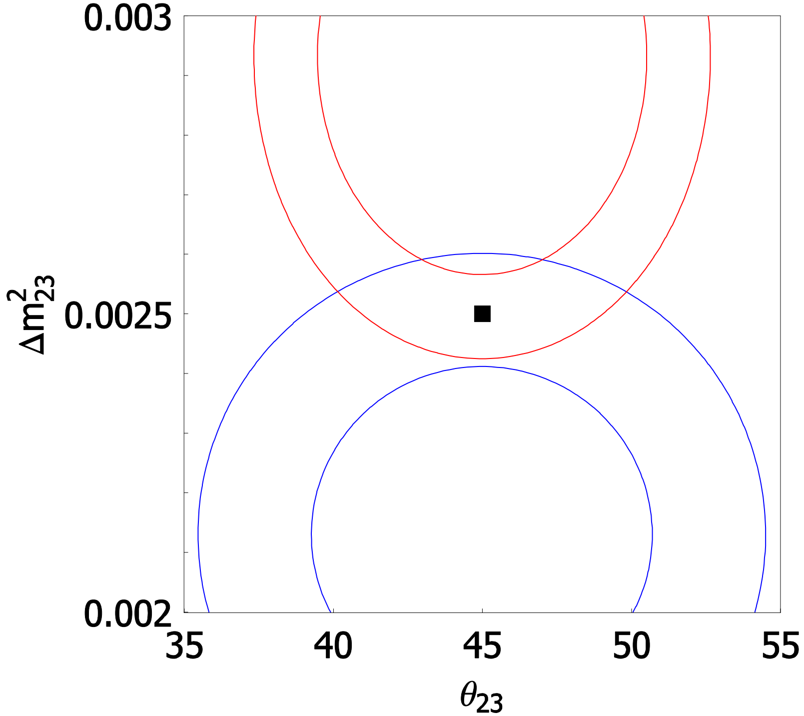
$\delta = 0^o$

$\langle E_\nu \rangle = 0.27 GeV$

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

The importance of energy resolution

T2K-I



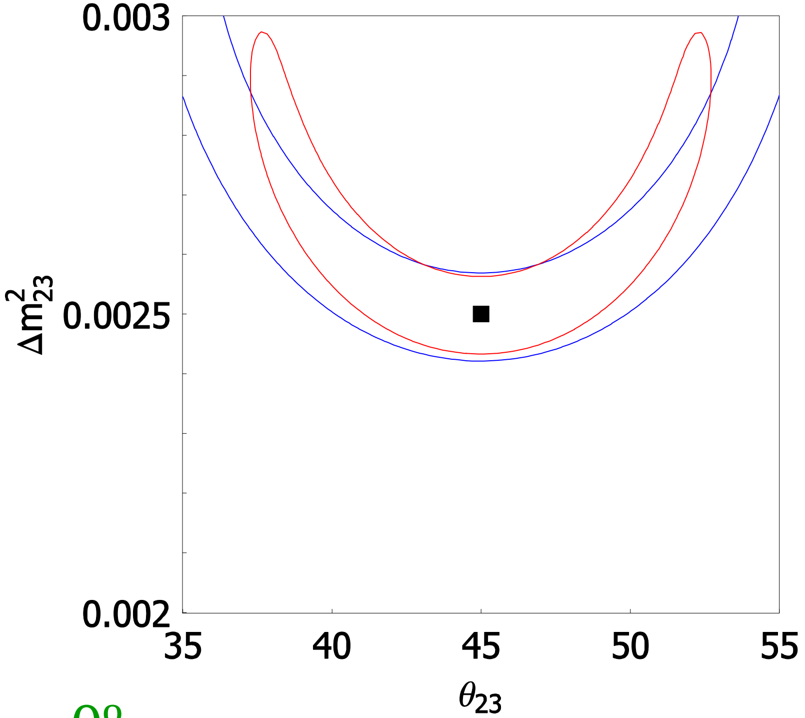
E1 = 0.4 - 0.6GeV

E2 = 0.6 - 0.8GeV

$\theta_{13} = 0^o$

$\delta = 0^o$

SPL

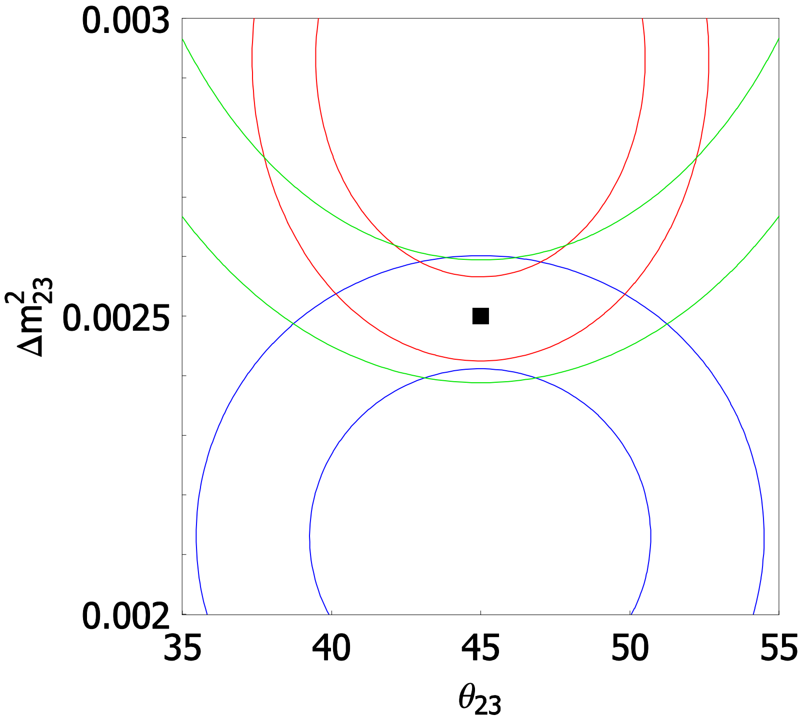


$\langle E_\nu \rangle = 0.27\text{GeV}$

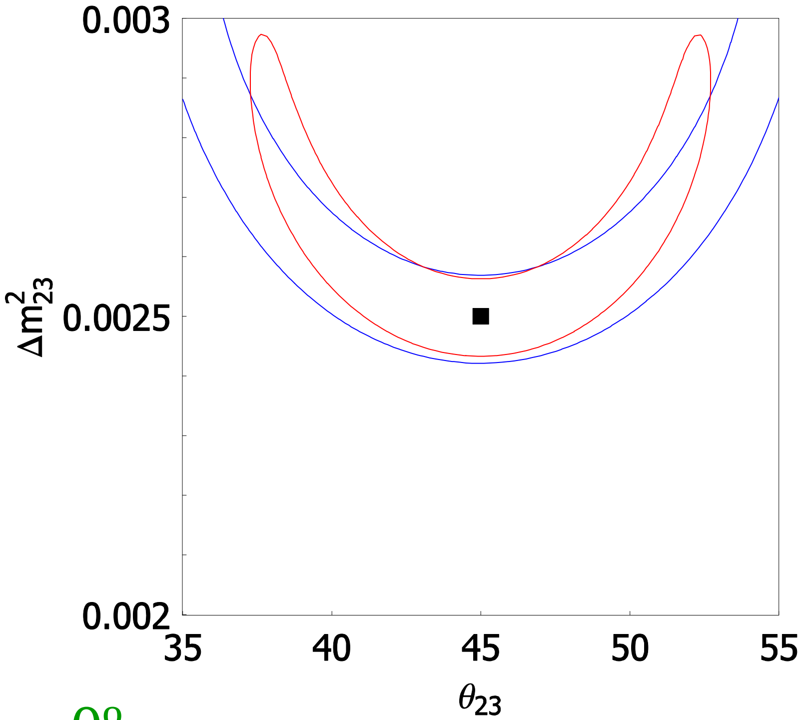
$\langle E_{\bar{\nu}} \rangle = 0.25\text{GeV}$

The importance of energy resolution

T2K-I



SPL



E1 = 0.4 - 0.6GeV

E2 = 0.6 - 0.8GeV

E3 = 0.8 - 1.0GeV

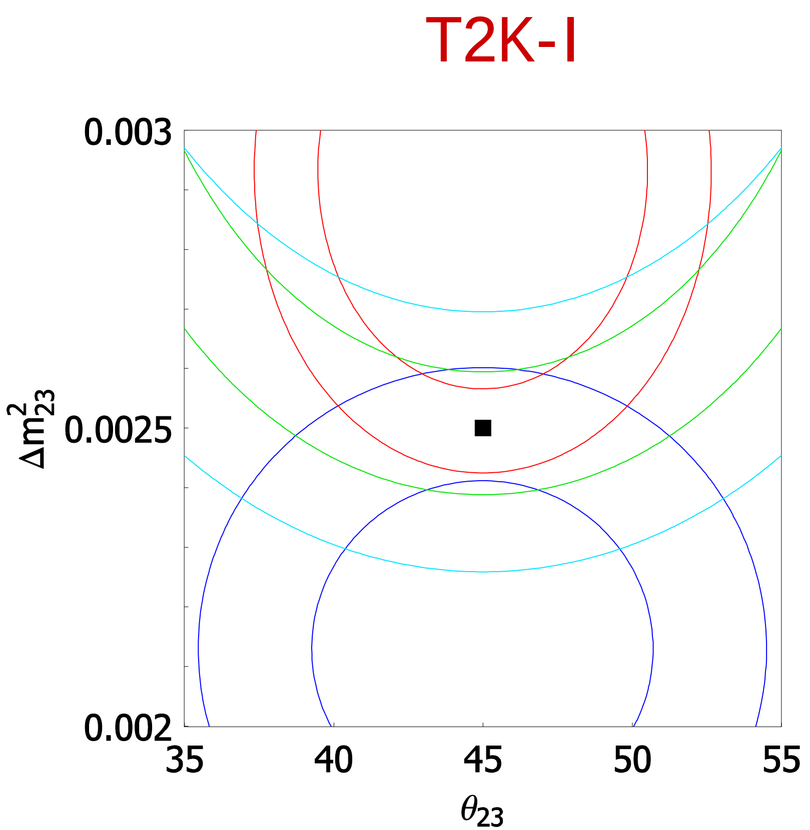
$\theta_{13} = 0^{o}$

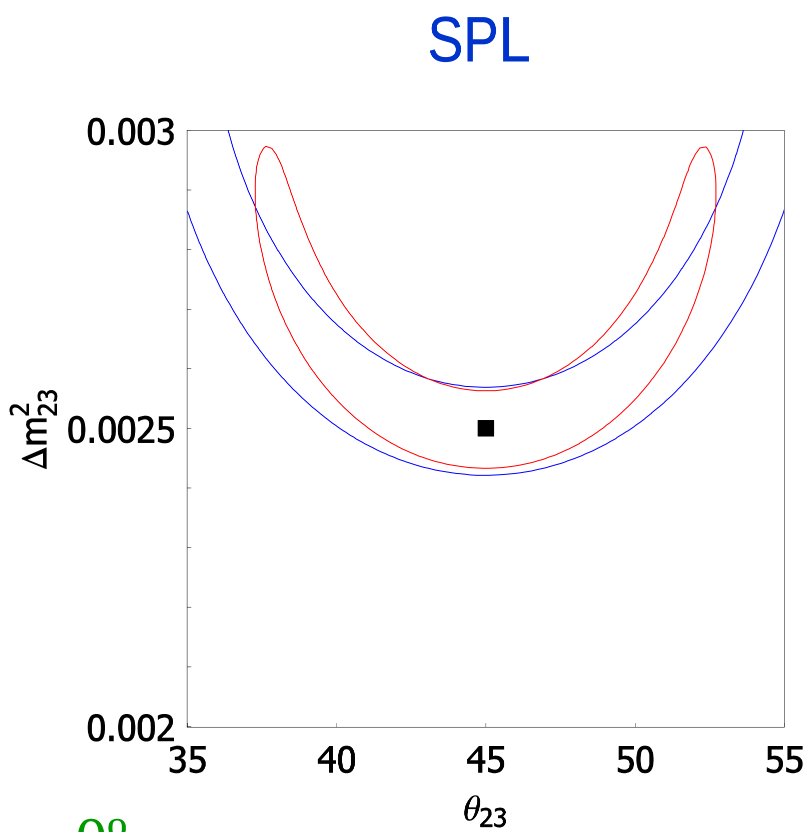
$\delta = 0^{o}$

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

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

The importance of energy resolution





E1 = 0.4 - 0.6GeV

E2 = 0.6 - 0.8GeV

E3 = 0.8 - 1.0GeV

E4 = 1.0 - 1.2GeV

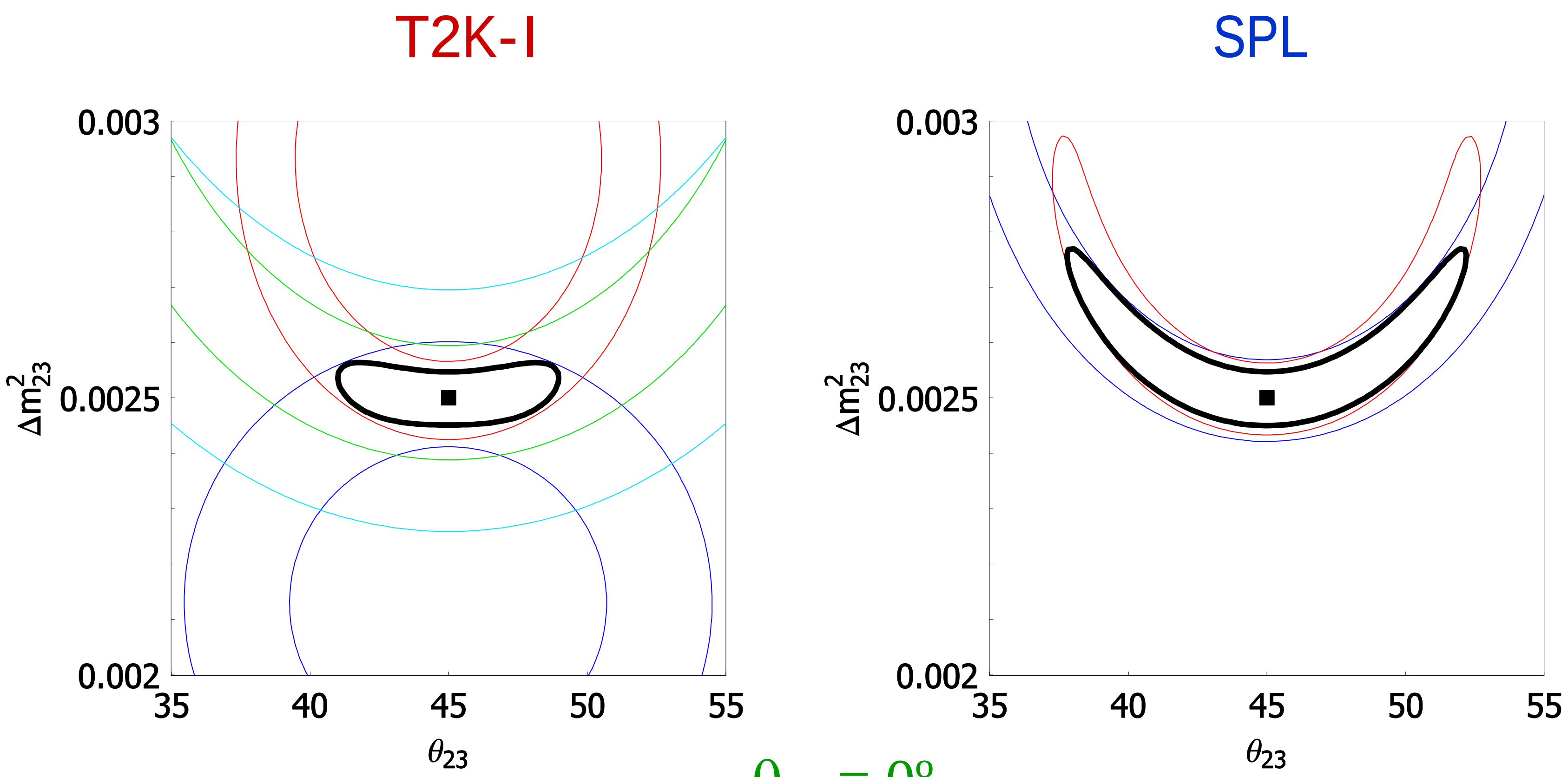
$\theta_{13} = 0^o$

$\delta = 0^o$

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

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

The importance of energy resolution



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

$\theta_{13} = 0^o$
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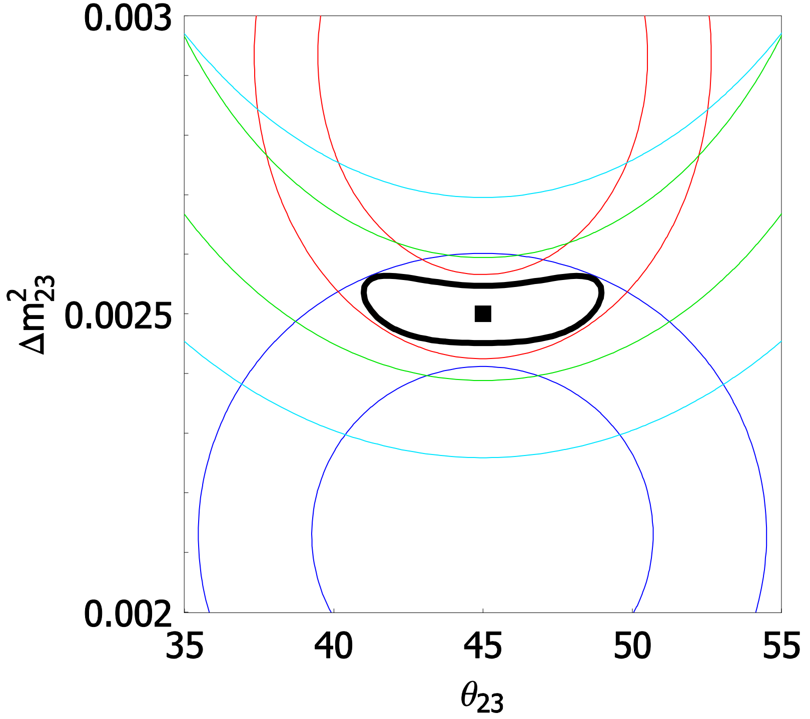
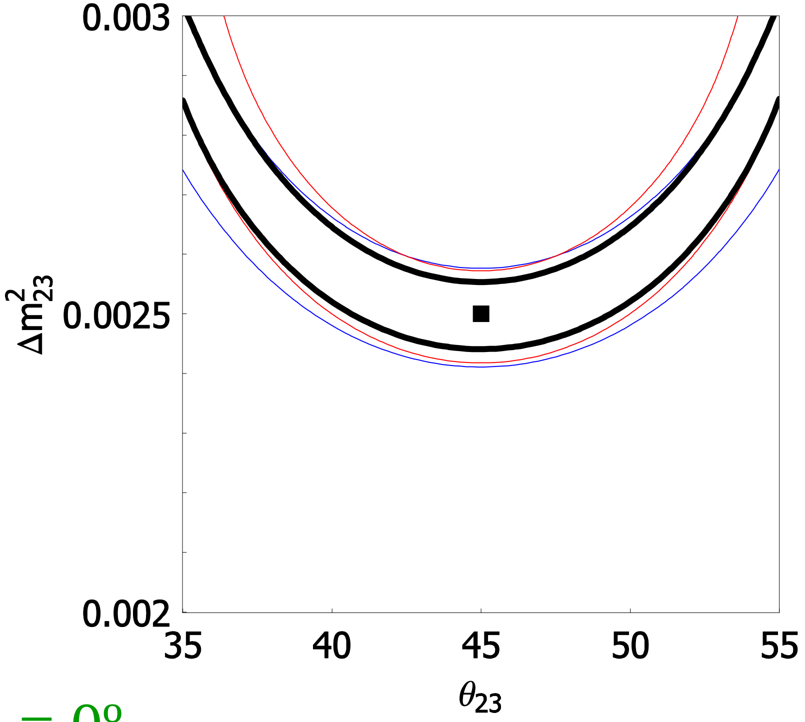
The importance of energy resolution





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

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

$\langle E_\nu \rangle = 0.29\text{GeV}$

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

The ν_μ disappearance channel

$$P(\nu_\mu \to \nu_\mu) = 1 - (\sin^2 2\theta_{23} - s_{23}^2 \sin^2 2\theta_{13} \cos^2 2\theta_{23}) \sin^2\left(\frac{\Delta_{atm} L}{2}\right)$$
$$- \left(\frac{\Delta_{sol} L}{2}\right) [s_{12}^2 \sin^2 2\theta_{23} + \tilde{J} s_{23}^2 \cos\delta] \sin(\Delta_{atm} L)$$
$$- \left(\frac{\Delta_{sol} L}{2}\right)^2 [c_{23}^4 \sin^2 2\theta_{12} + s_{12}^2 \sin^2 2\theta_{23} \cos(\Delta_{atm} L)]$$

Where

$$\tilde{J} = \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$

$$\Delta_{sol} = \frac{\Delta m_{12}^2}{2E}$$

$$\sin 2\theta_{13} < 0.4$$

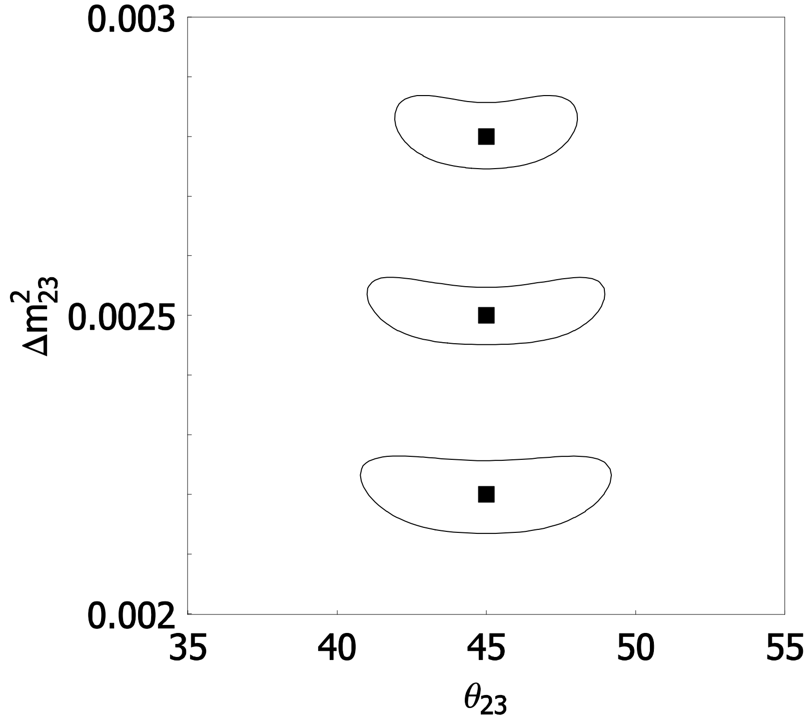
$$\Delta_{atm} = \frac{\Delta m_{23}^2}{2E}$$

$$\left(\frac{\Delta_{sol} L}{2}\right) \cong 0.05$$

E. K. Akhmedov *et al.* hep-ph/0402175
A. Donini *et al.* hep-ph/0411402

The sign degeneracy

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



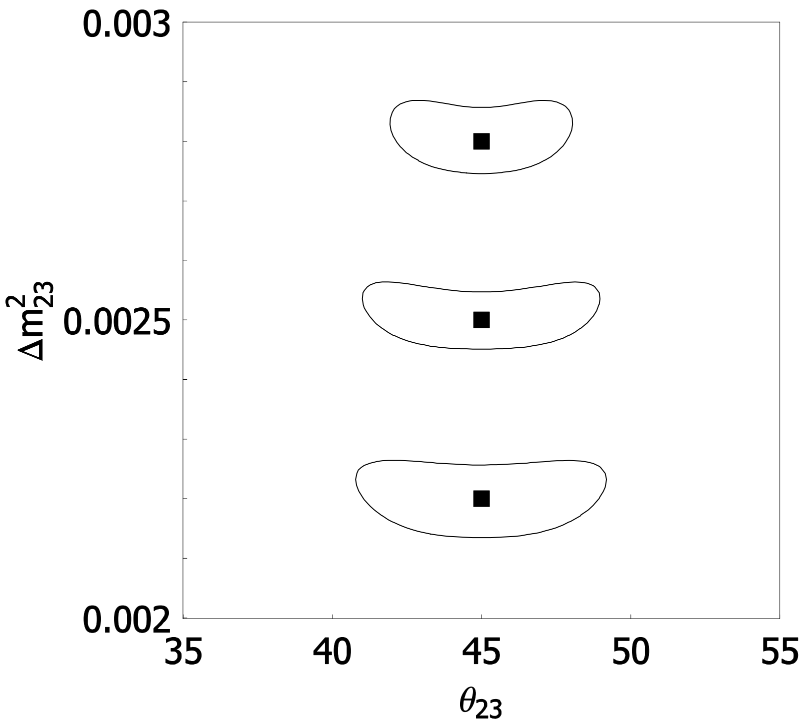
$$P(\nu_\mu \to \nu_\mu) = 1 - (\sin^2 2\theta_{23}) \sin^2\left(\frac{\Delta_{atm} L}{2}\right)$$

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

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

The sign degeneracy

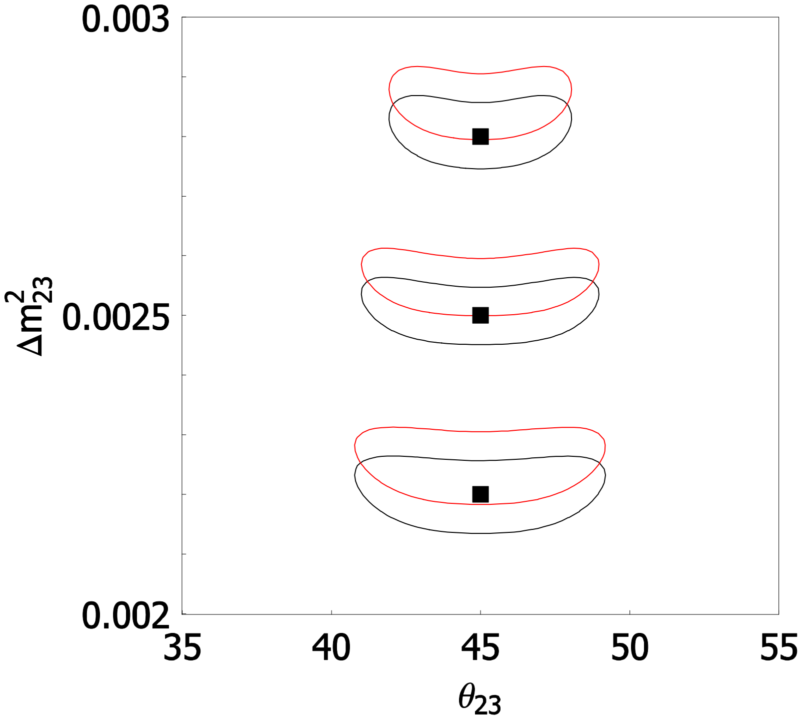
Input:
$\theta_{13} = 0^o$
$\delta = 0^o$



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

The sign degeneracy

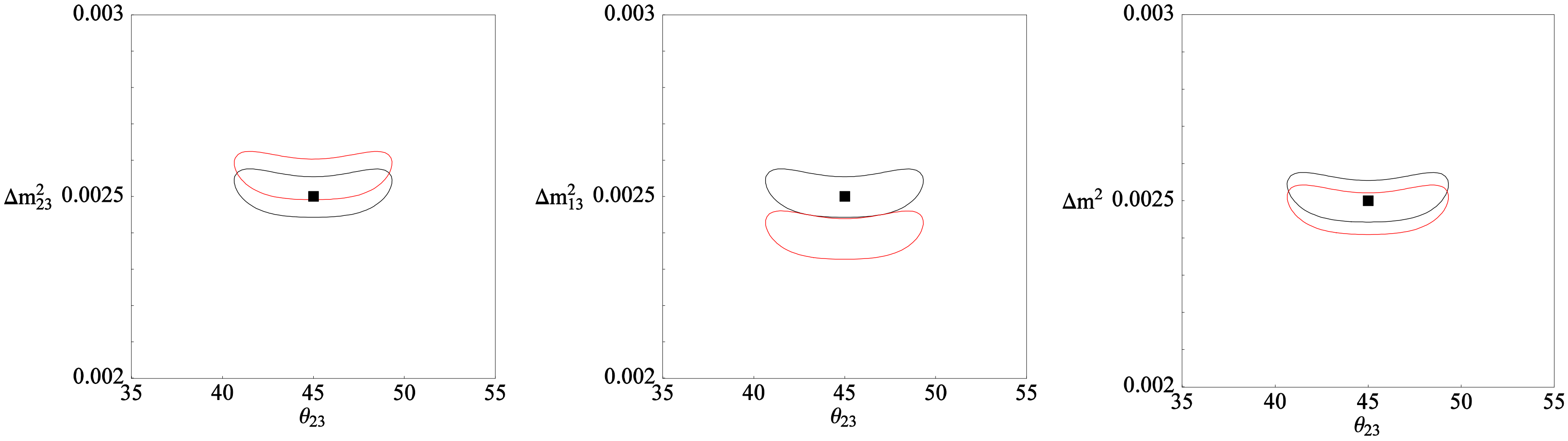
Input:
$\theta_{13} = 0^o$
$\delta = 0^o$



Fit assuming inverted hierarchy

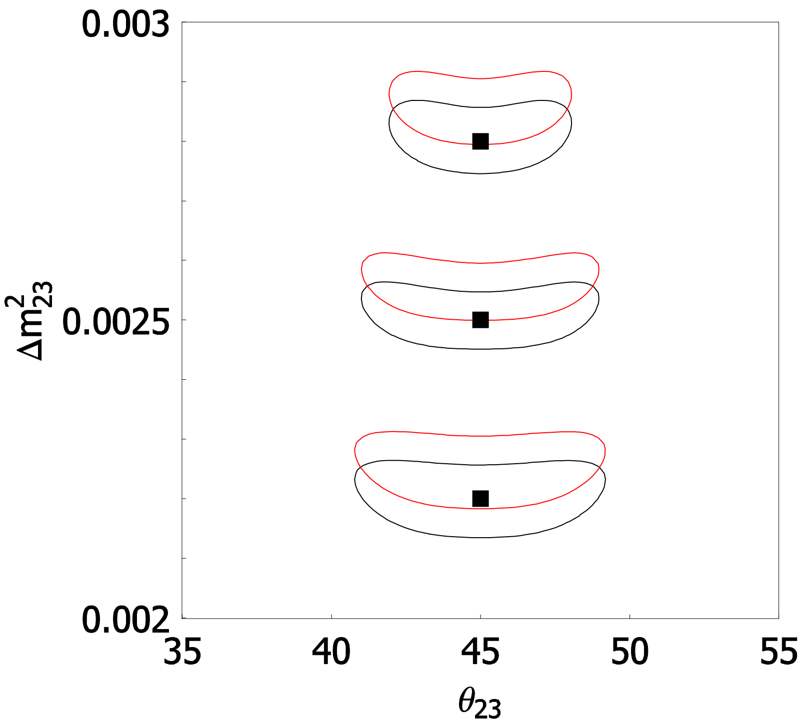
$$P(\nu_\mu \to \nu_\mu) = 1 - (\sin^2 2\theta_{23}) \sin^2\left(\frac{\Delta_{atm} L}{2}\right) - \left(\frac{\Delta_{sol} L}{2}\right) [s_{12}^2 \sin^2 2\theta_{23}] \sin(\Delta_{atm} L) + O\left(\frac{\Delta_{sol} L}{2}\right)^2$$

The sign degeneracy



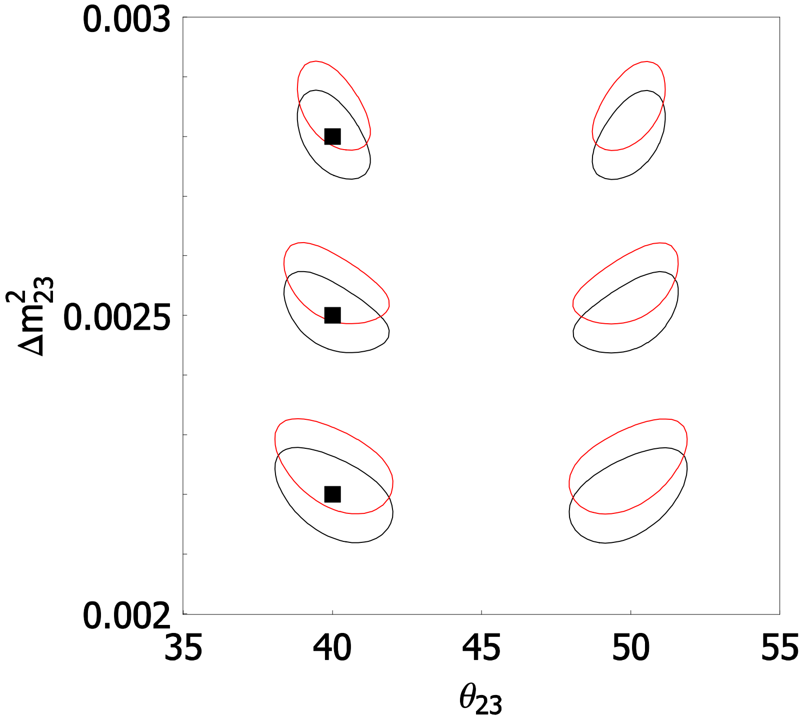
The octant degeneracy

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



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

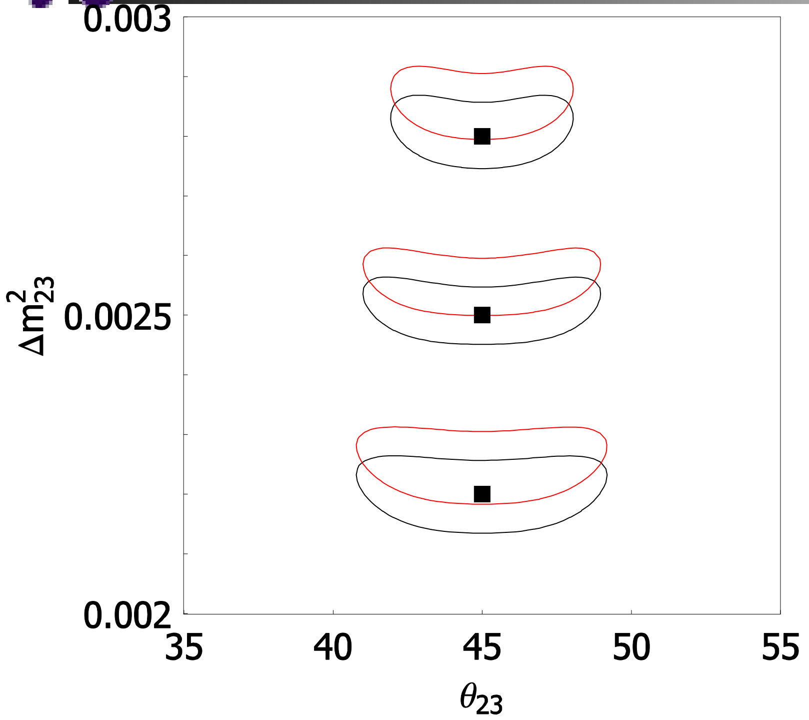
The octant degeneracy



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

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

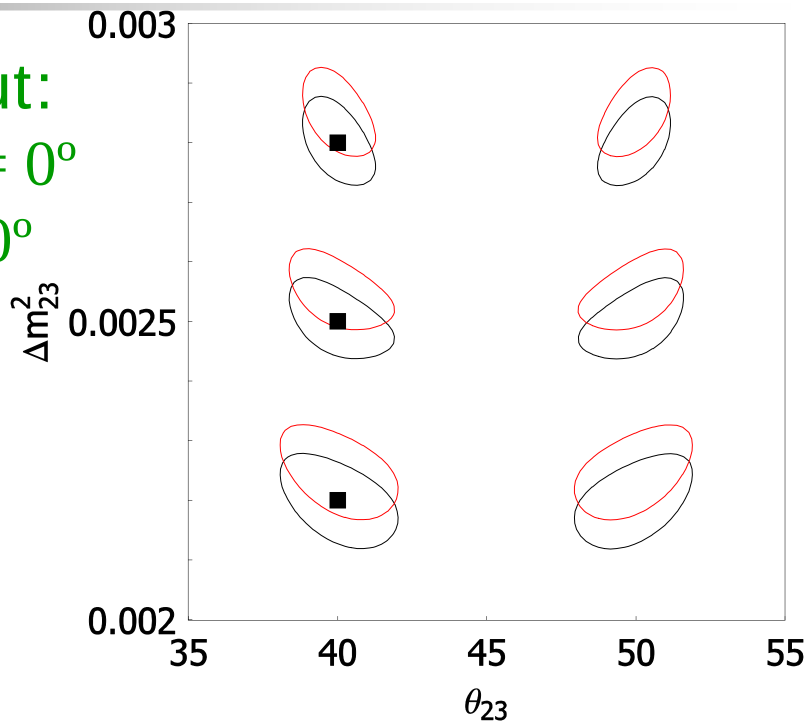
The effect of θ_{13}



Input:

$\theta_{13} = 0^o$

$\delta = 0^o$



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

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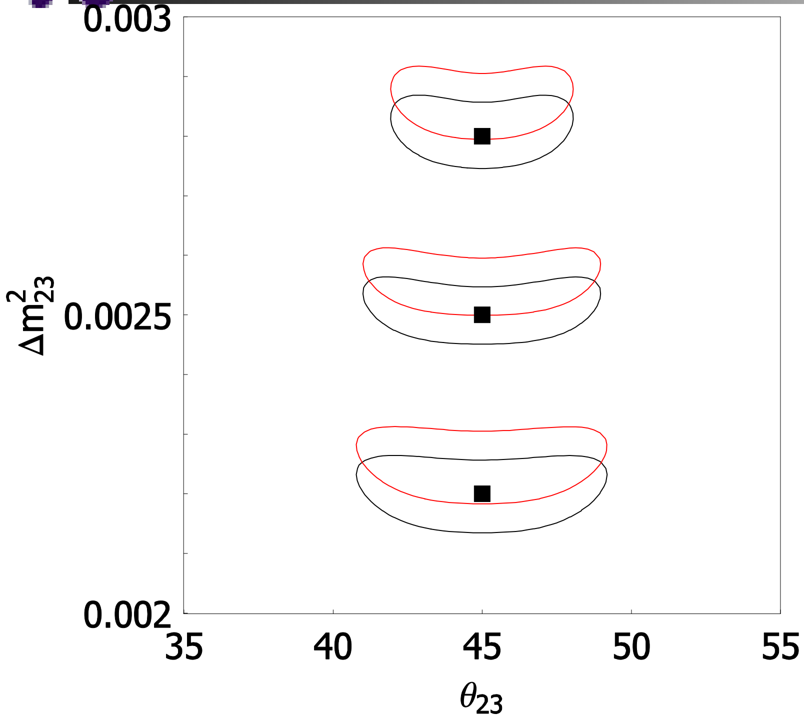
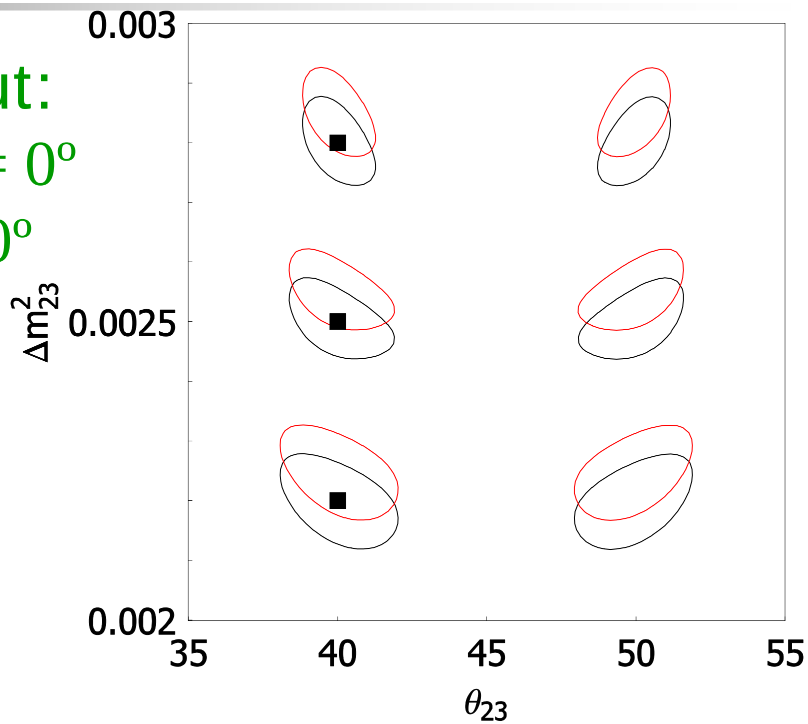


Input:
$\theta_{13} = 0^o$
$\delta = 0^o$



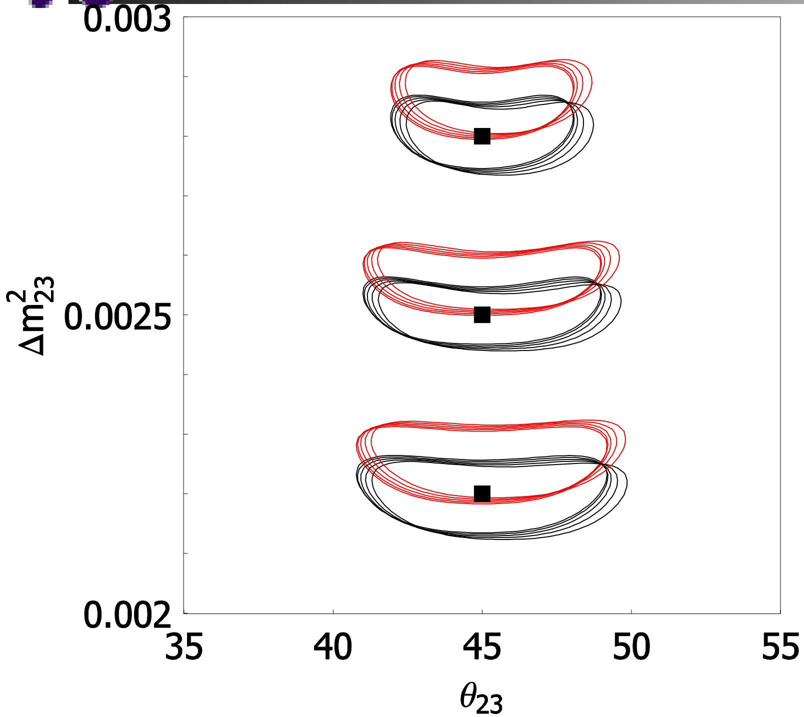
Assuming $\theta_{13} = 0^o$

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

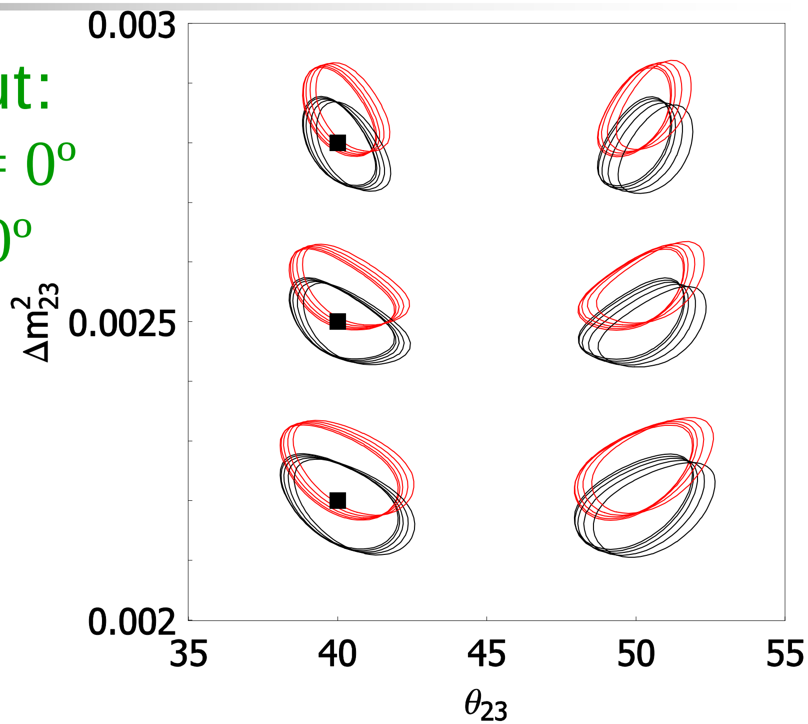
$$- \left(\frac{\Delta_{sol} L}{2}\right) [s_{12}^2 \sin^2 2\theta_{23} + [s_{23}^2 \cos\delta] \sin(\Delta_{atm} L)$$

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

The effect of θ_{13}



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



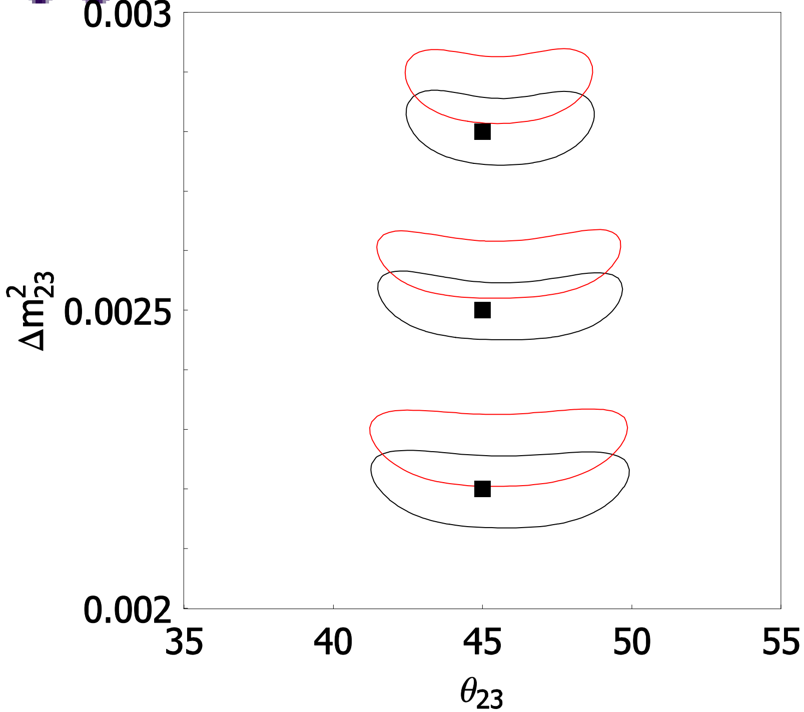
Assuming $\theta_{13} = 0^o, 2^o, 4^o, 6^o, 8^o$

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

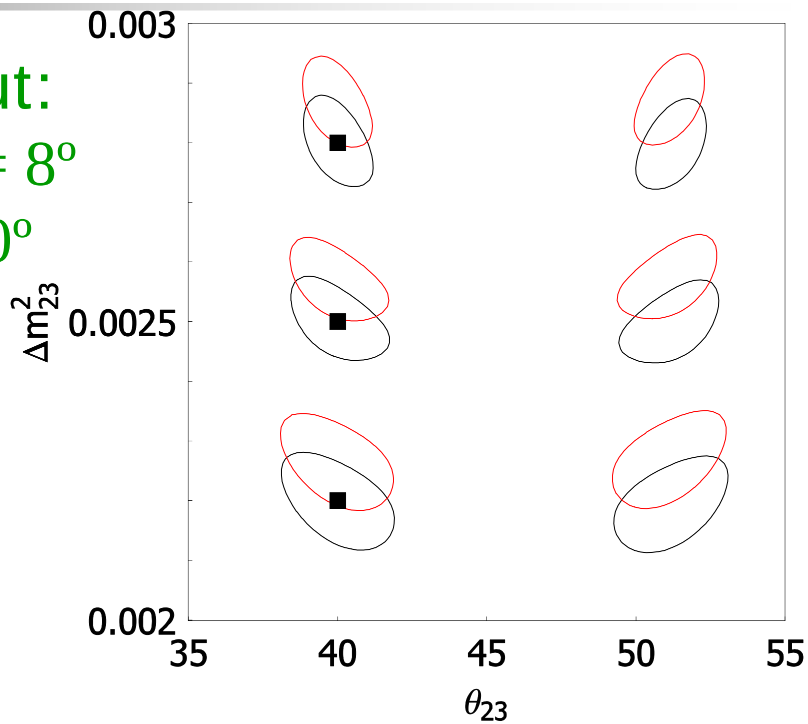
$$- \left(\frac{\Delta_{sol} L}{2}\right) [s_{12}^2 \sin^2 2\theta_{23} + 2J s_{23}^2 \cos\delta] \sin(\Delta_{atm} L)$$

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

The effect of δ



Input:
$\theta_{13} = 8^o$
$\delta = 0^o$



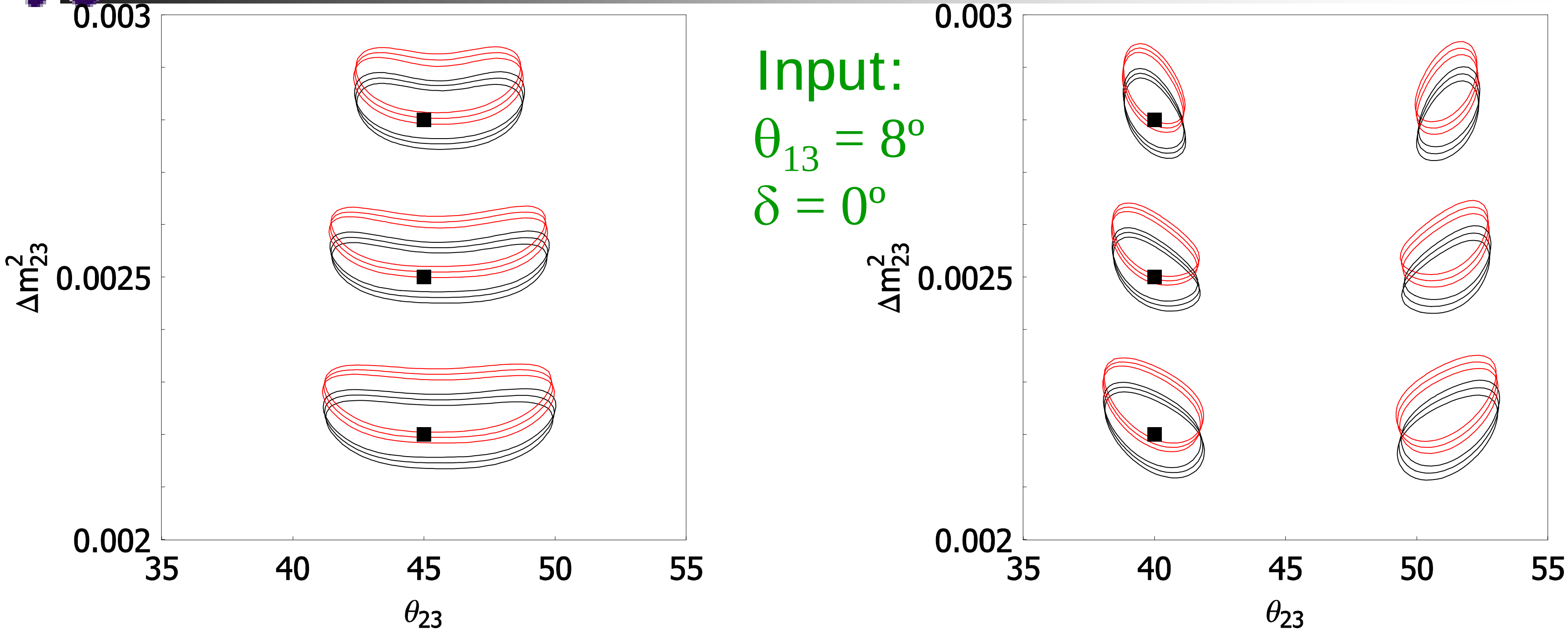
Assuming $\delta = 0^o$

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

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

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

The effect of δ



Input:
$\theta_{13} = 8^o$
$\delta = 0^o$

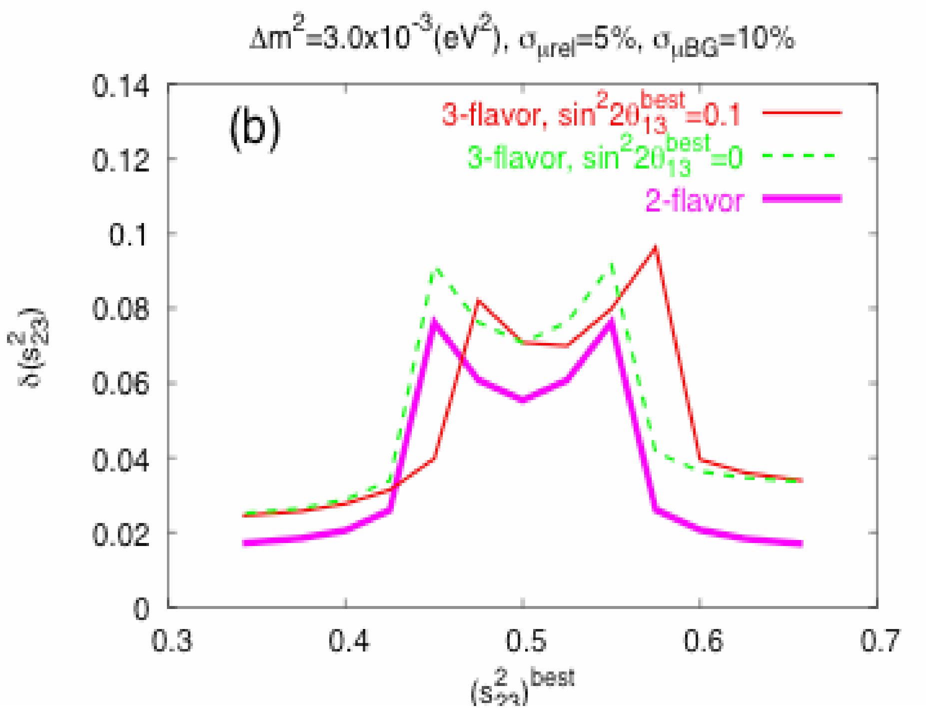
Assuming $\delta = 0^o, 90^o, 180^o$

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

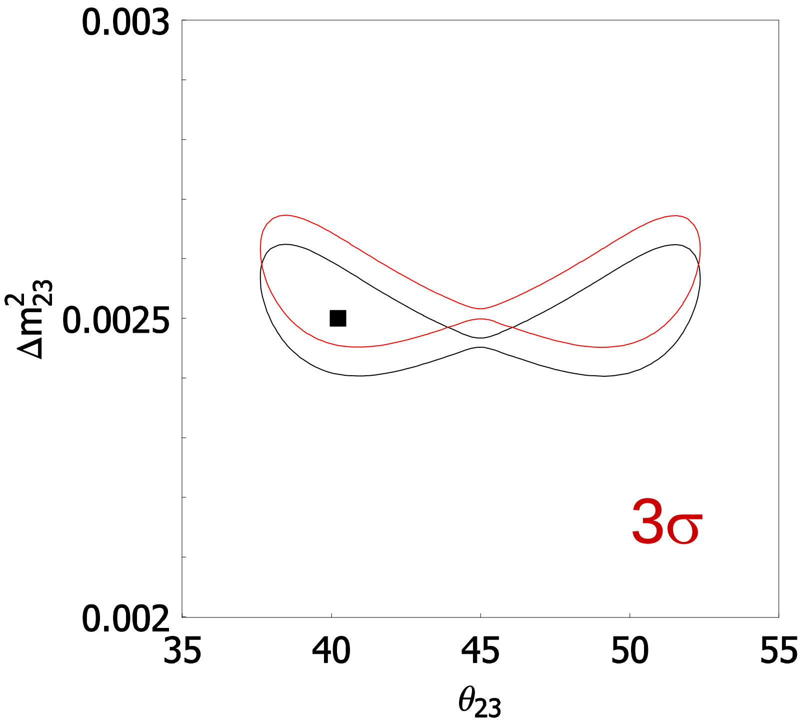
$$- \left(\frac{\Delta_{sol} L}{2}\right) [s_{12}^2 \sin^2 2\theta_{23} + \tilde{J} s_{23}^2 \cos\delta] \sin(\Delta_{atm} L)$$

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

T2K-I errors revised



Minakata *et al.* hep-ph/0406073



Antusch *et al.* hep-ph/0404268

$\Delta m^2 = (1.7 - 3.5)\cdot 10^{-3}$ eV^2

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

$\Delta m^2 = (2.43 - 2.60)\cdot 10^{-3}$ eV^2

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

$\Delta m^2 = (-2.63 - -2.49)\cdot 10^{-3}$ eV^2

$\Delta m^2 = (2.42 - 2.61)\cdot 10^{-3}$ eV^2

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

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

$\Delta m^2 = (-2.64 - -2.47)\cdot 10^{-3}$ eV^2

Preliminar analysis at the NuFactory

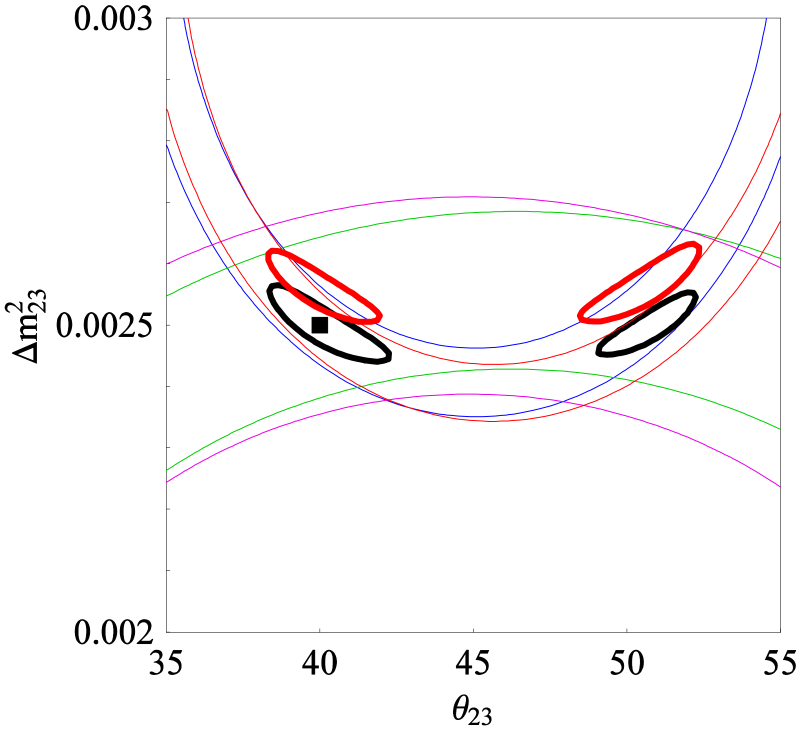
5yr ν_μ + 5yr $\bar{\nu}_\mu$ exposure with a 40Kt iron calorimeter for the NF

- 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%

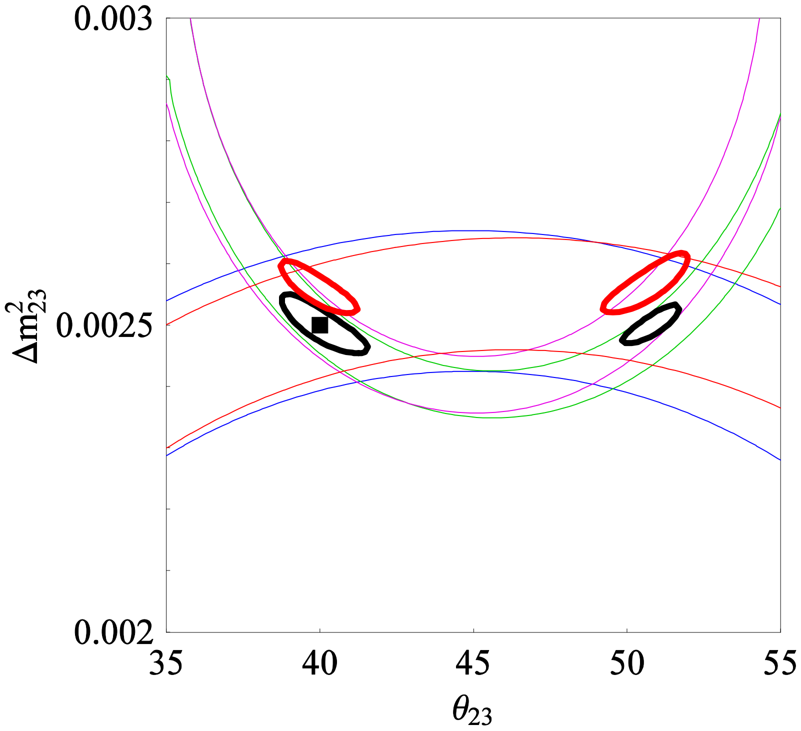
"Cervera *et al.* hep-ph/0002108"

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

Neutrino Factory



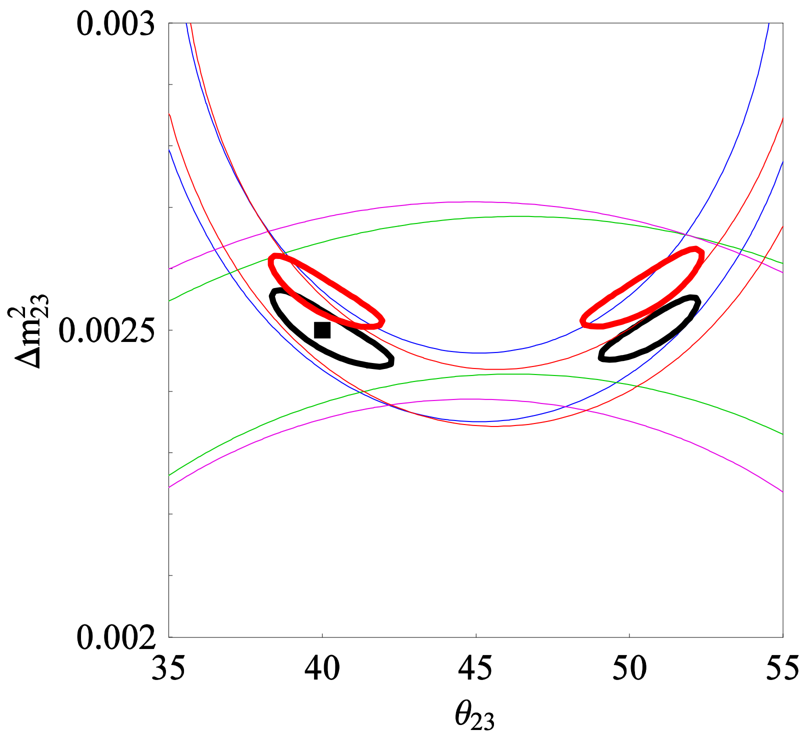
E = 50 GeV
L = 3000 Km



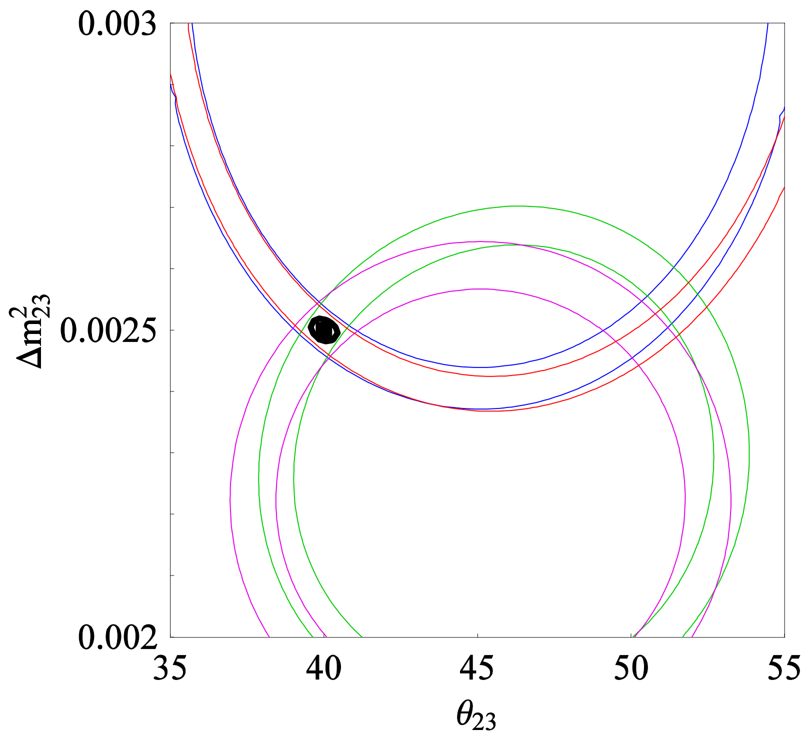
E = 20 GeV
L = 3000 Km

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

Neutrino Factory



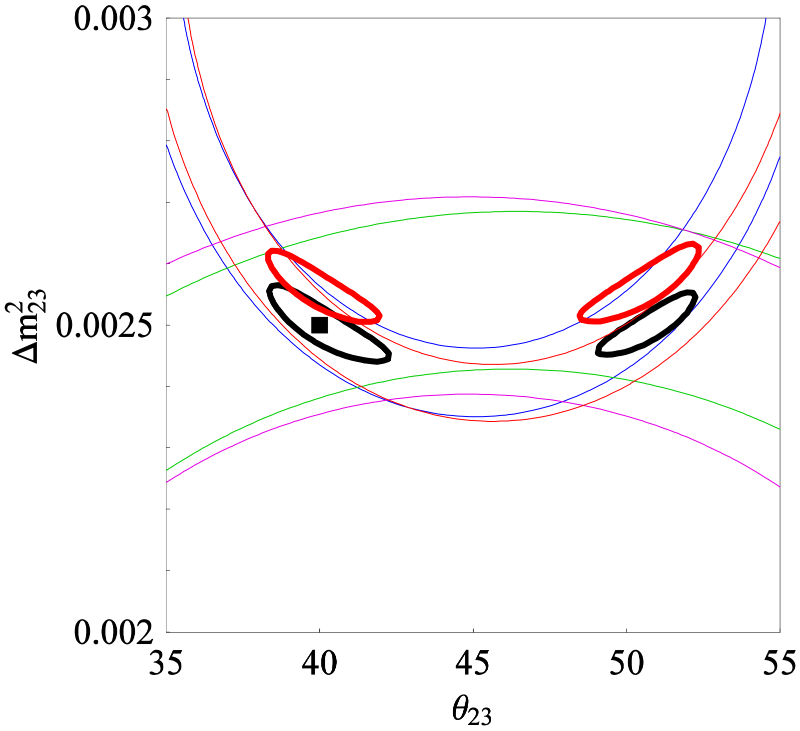
E = 50 GeV
L = 3000 Km

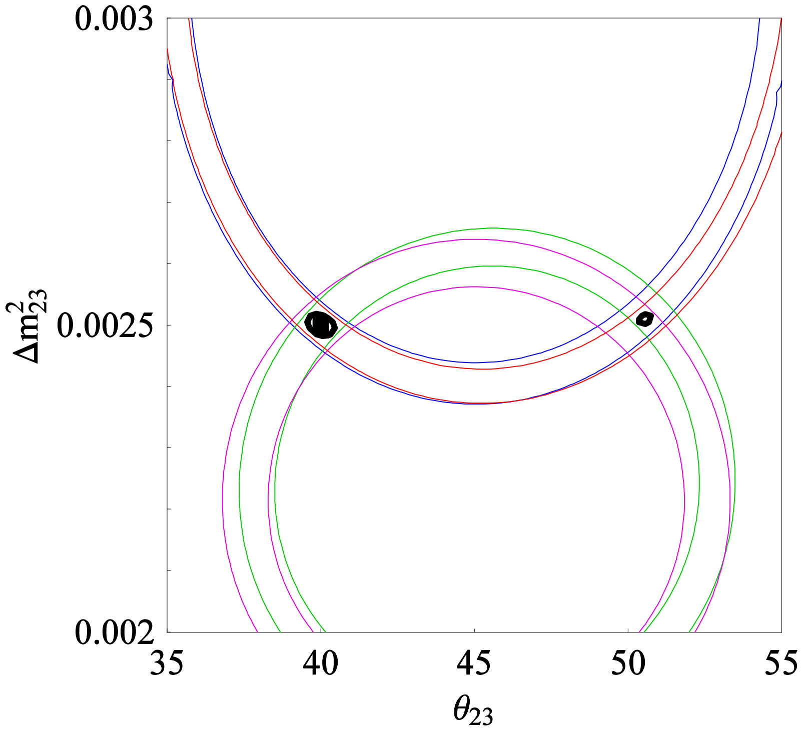


E = 50 GeV
L = 7000 Km

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

Neutrino Factory



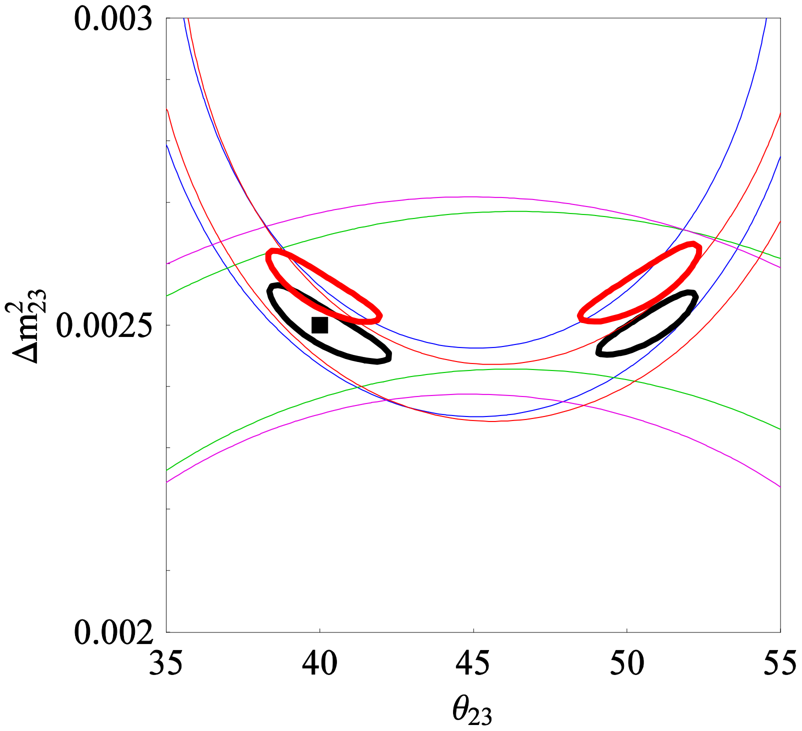


E = 50 GeV
L = 3000 Km

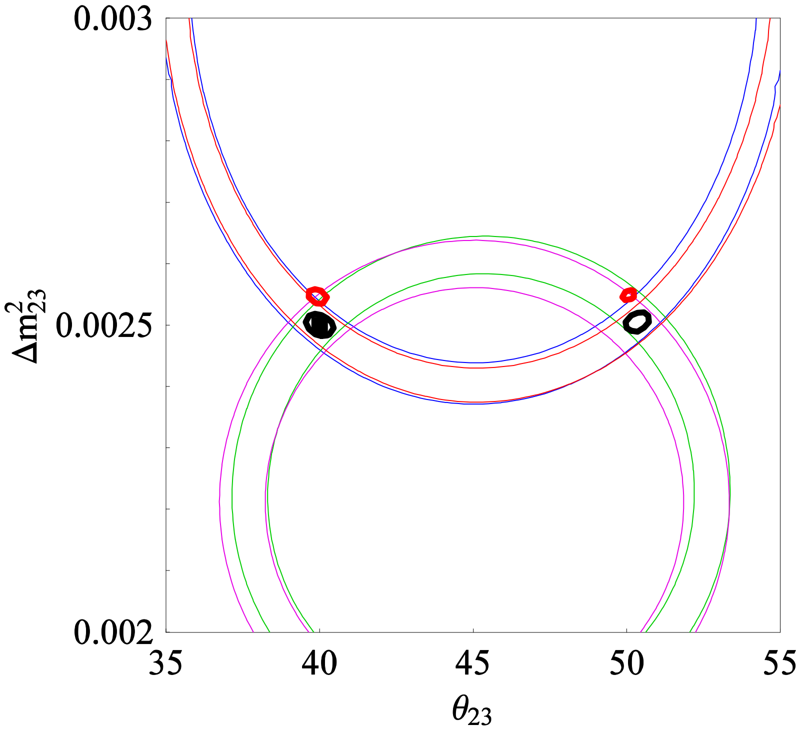
E = 50 GeV
L = 7000 Km

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

Neutrino Factory



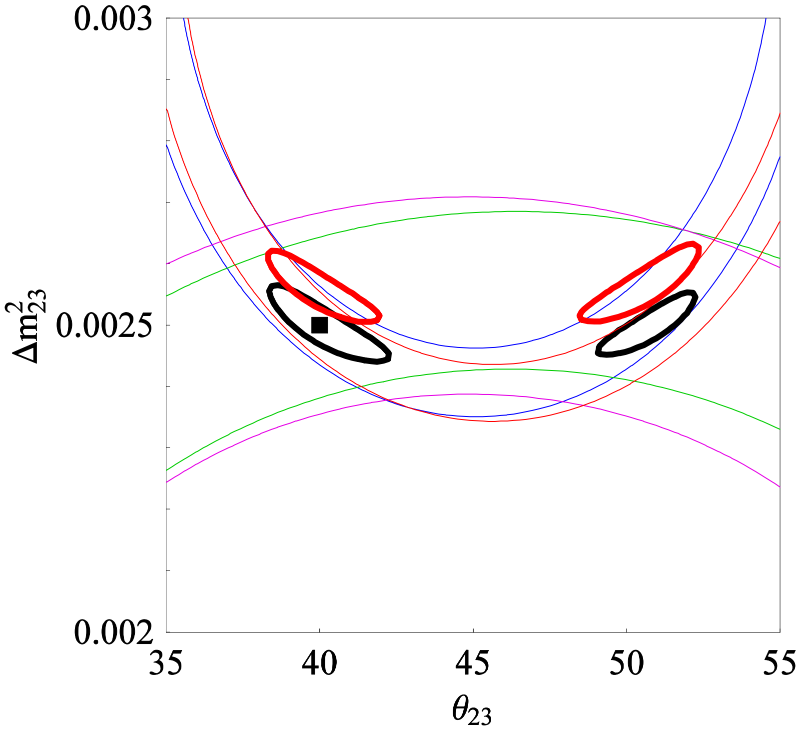
E = 50 GeV
L = 3000 Km

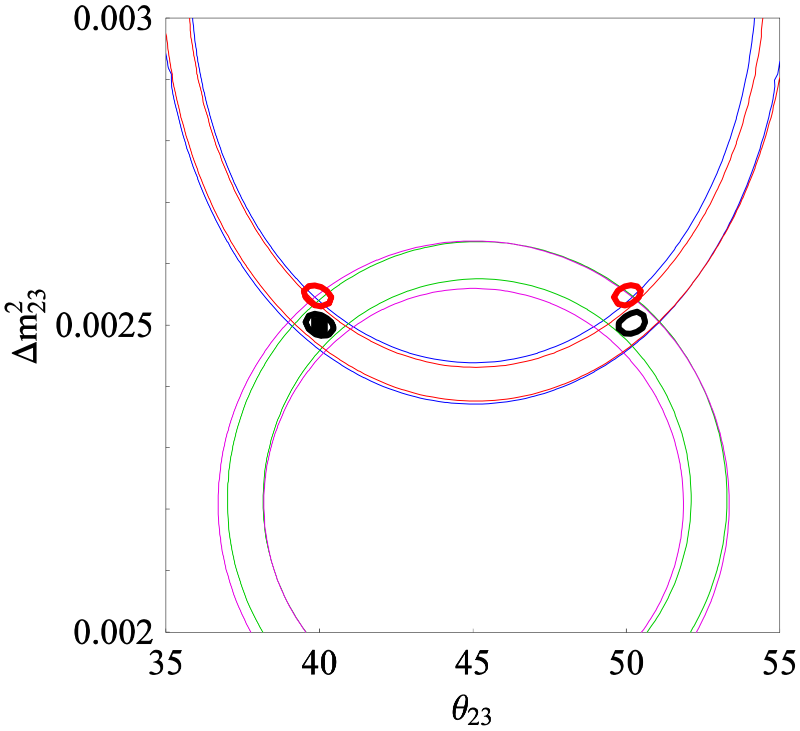


E = 50 GeV
L = 7000 Km

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

Conclusions

- The measurement of θ_{13} and δ will rely heavily on an improvement of the measure of θ_{23} and Δm^2_{23}

  See Meloni's talk
- Precision measurements of θ_{23} and Δm^2_{23} need energy resolution and events above and below the oscillation peak
- SPL is clearly inadequate for the task. T2K-I is very good due to energy resolution and it can exclude maximal mixing for $\theta_{23} < 41^o$
- The NuFactory seems extremely promising but more study is needed (a very long baseline?)
- ν_μ disappearance can be combined with the appearance channel to solve degeneracies

Event Rates

NF 50GeV	B1	B2	B3	B4
No osc. N_μ	1137	15390	60590	147987
Signal μ^-	266	1297	16150	54128
Signal μ^+	153	751	9032	28635

New SPL	μ^-	μ^+
No osc. N_μ	79365	95511
Signal N_μ	8811	11347

4 energy bins of 5GeV
Between 0 – 20GeV

L=3000Km

Systematic dominated

L=130Km

Systematic dominated

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

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

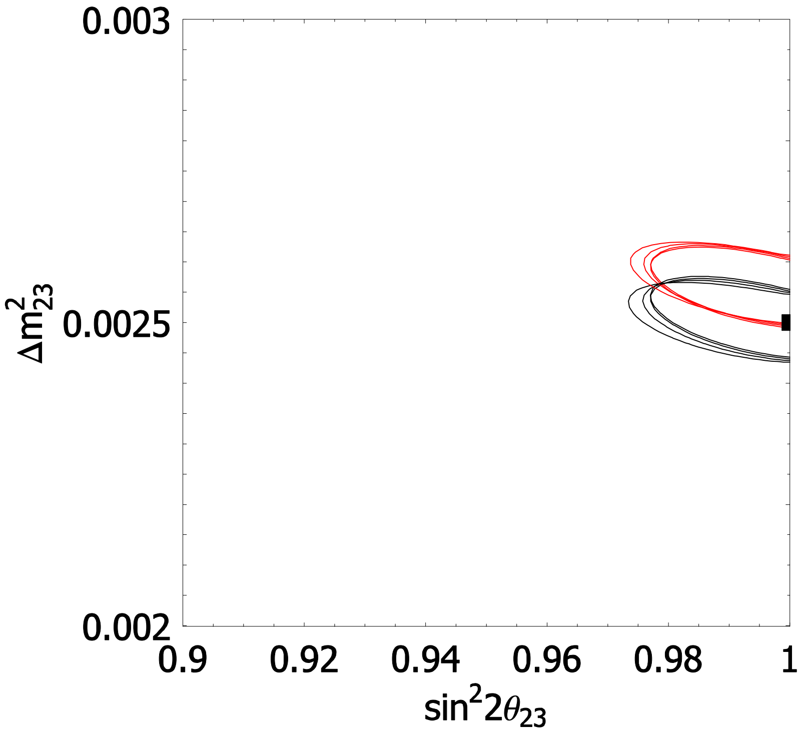
Event Rates

NF 20GeV	B1	B2	B3	B4
No osc. N_μ	2598	31286	103756	196373
Signal μ^-	614	2574	27399	71472
Signal μ^+	337	1257	10415	11557

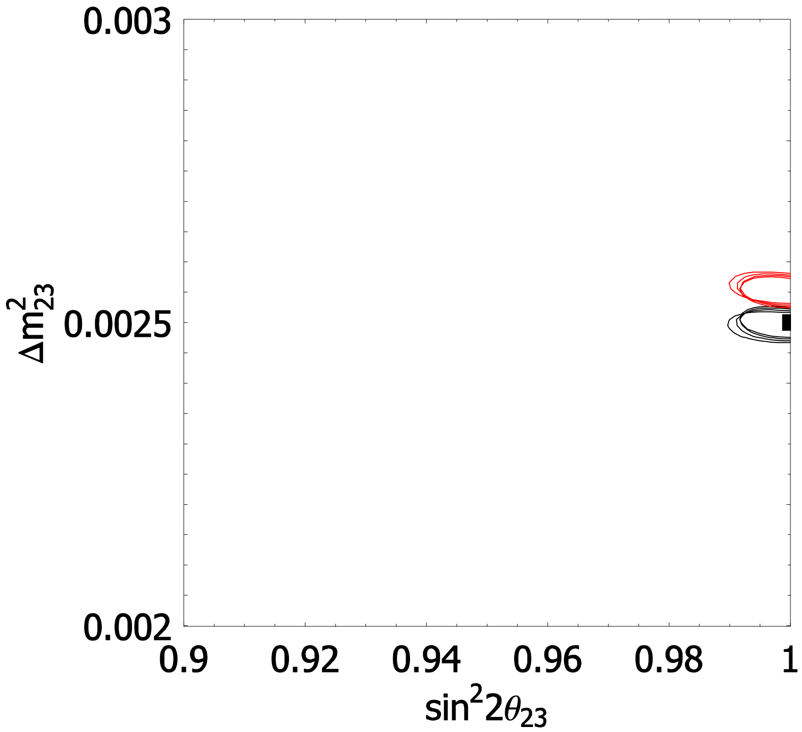
NF 50GeV 7000km	B1	B2	B3	B4
No osc. N_μ	209	2827	11129	27281
Signal μ^-	37	980	380	1328
Signal μ^+	21	569	215	697

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

T2K-2



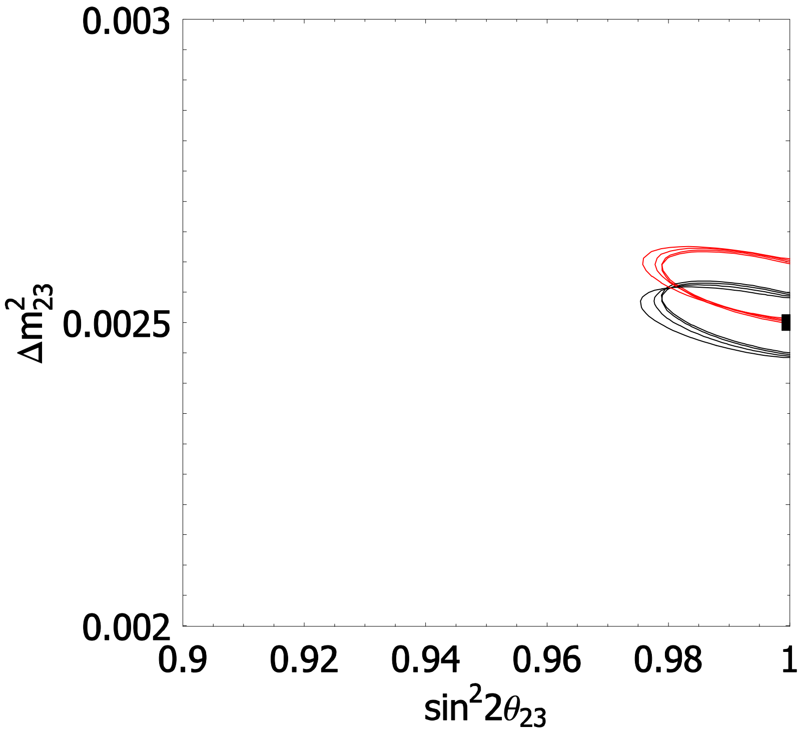
T2K-I



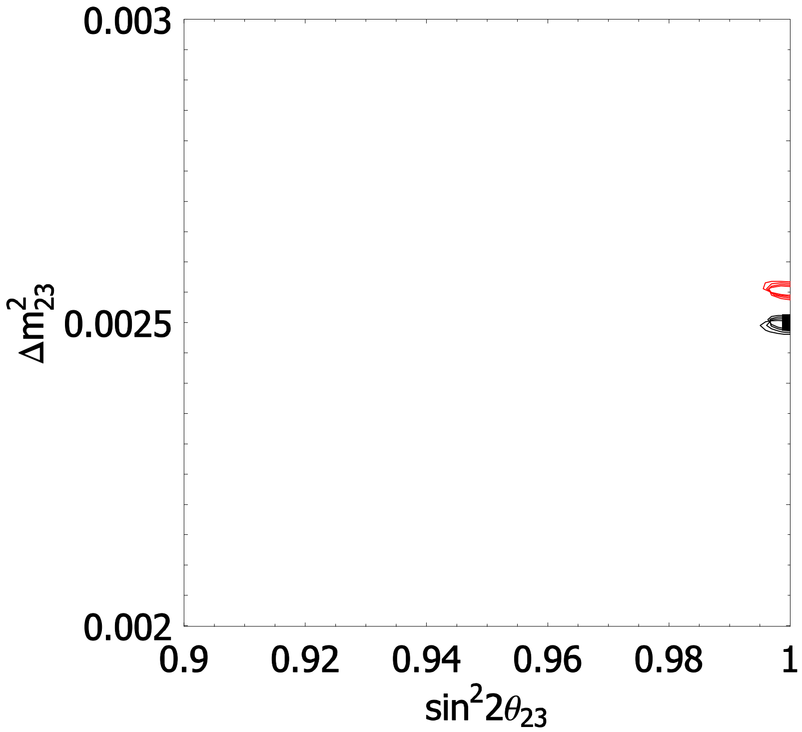
T2K-2

5% systematic error

T2K-2



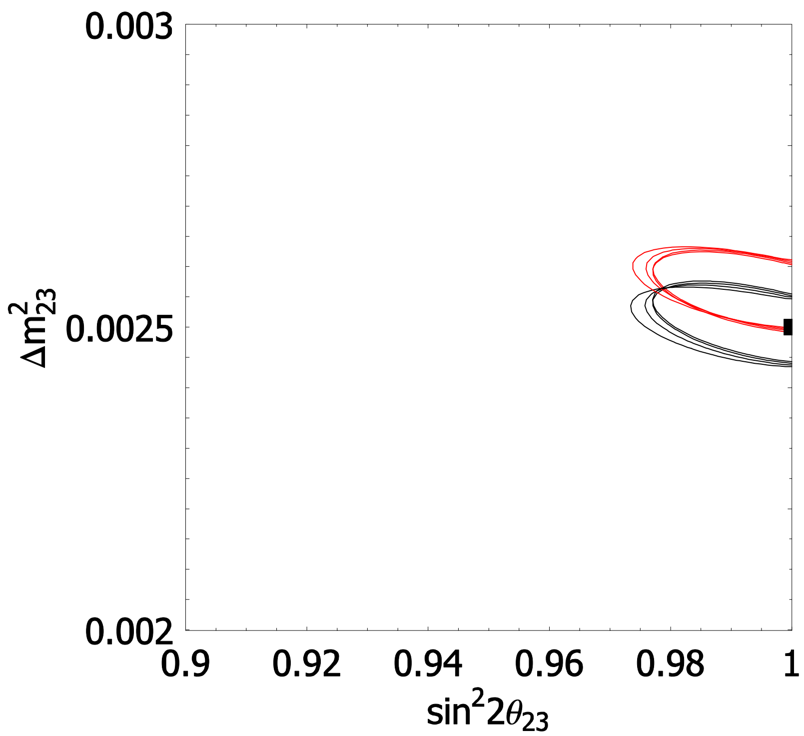
T2K-I

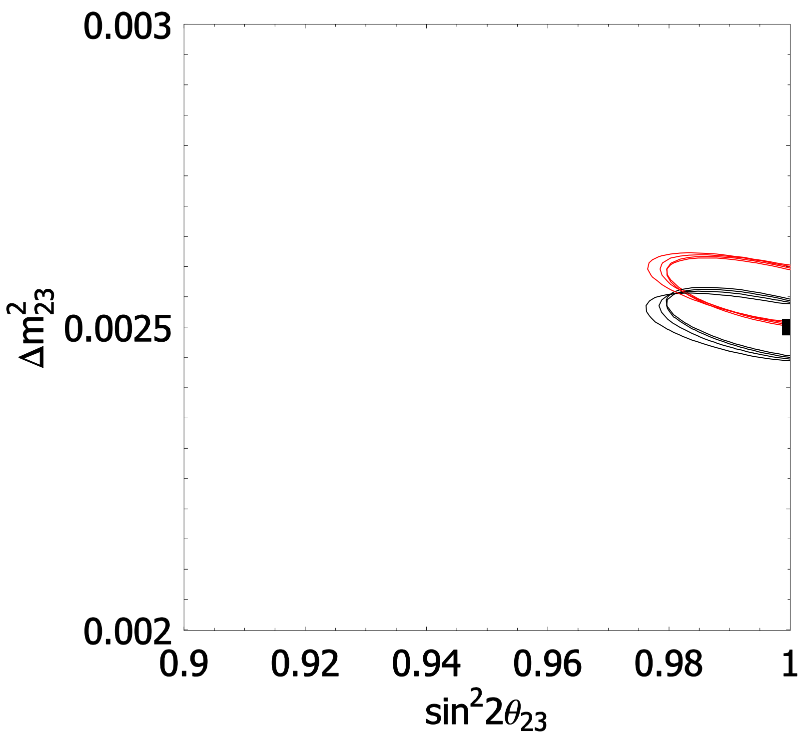


T2K-2

2% systematic error

No background and no systematic



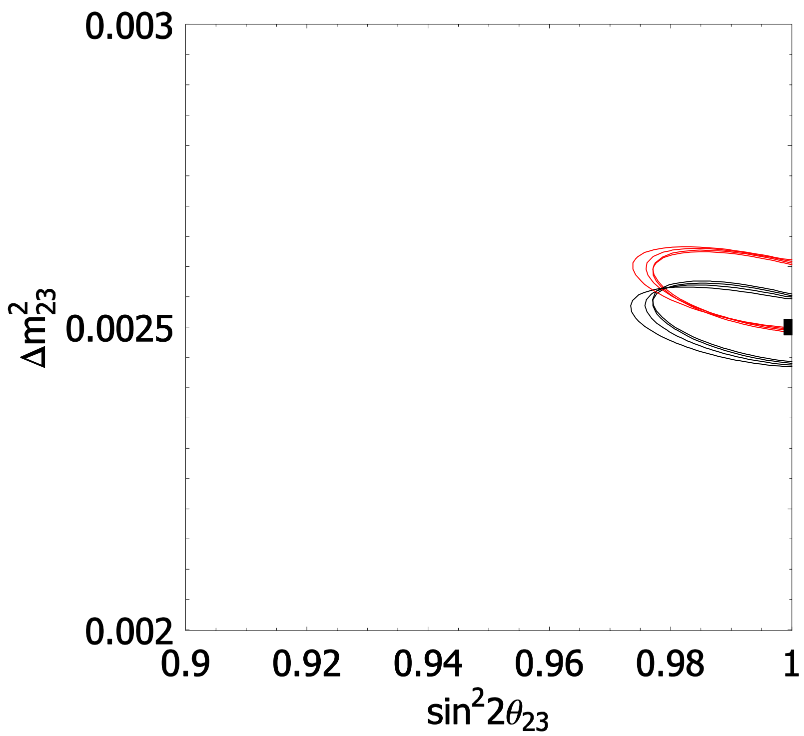


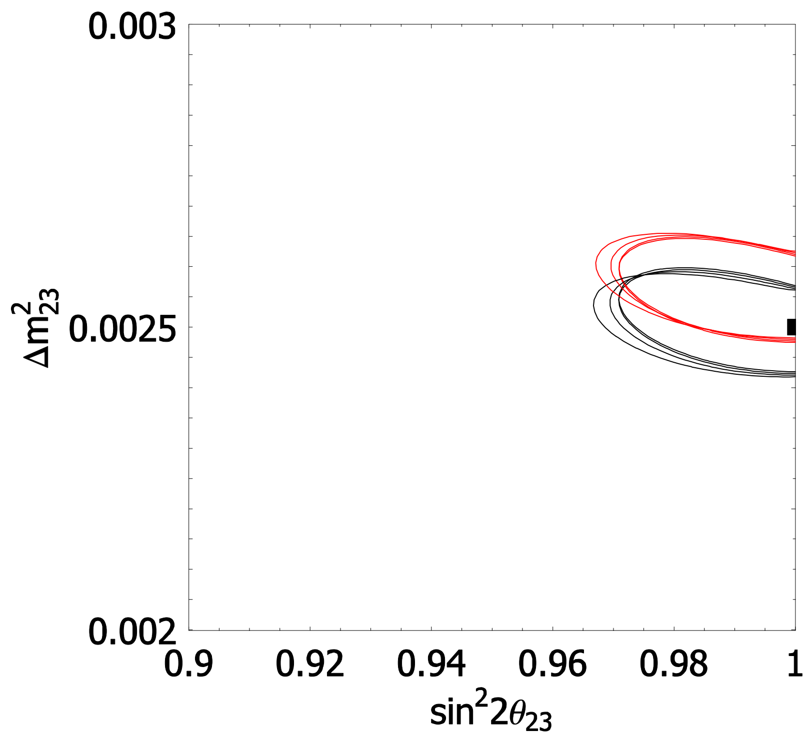
Systematic 5%
With Background

Systematic 0%
No Background

Errors dominated by statistics

10% systematic



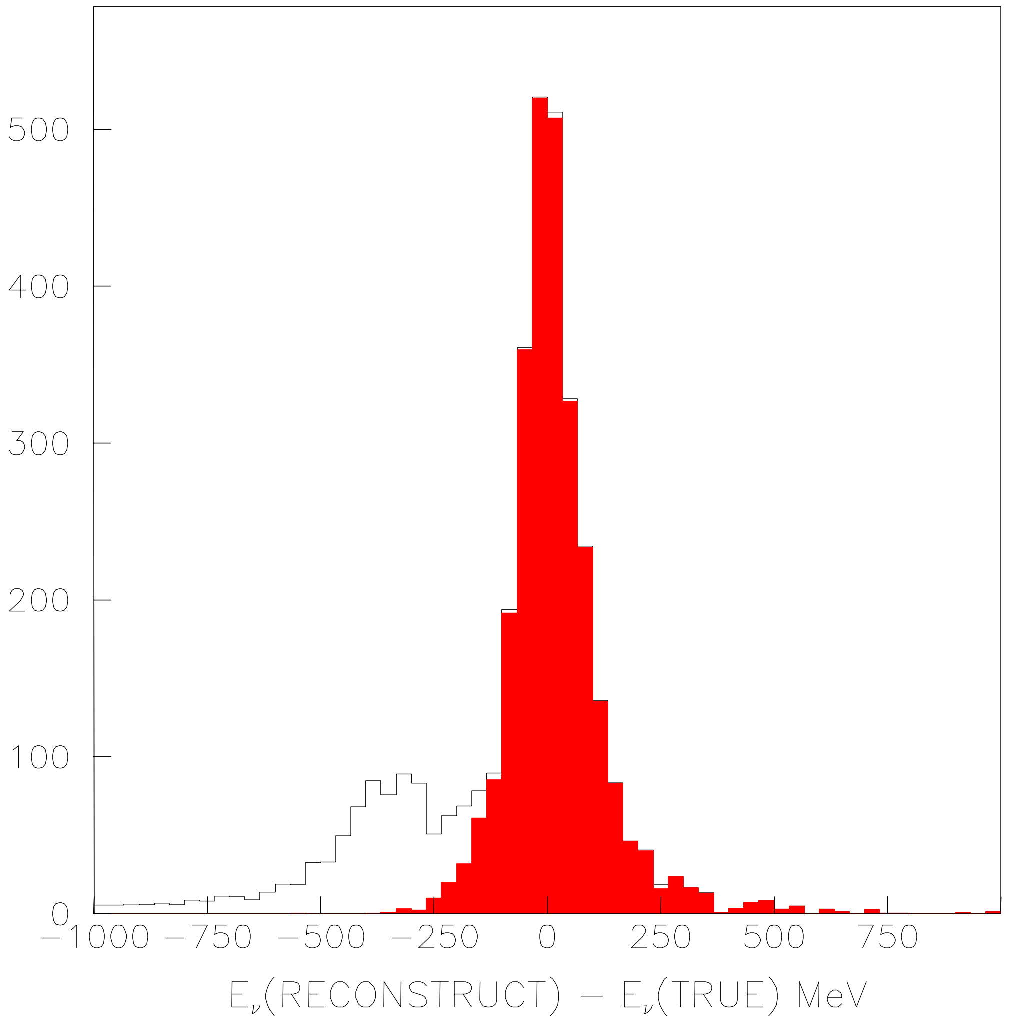


Systematic 5%

Systematic 10%

Errors dominated by statistics

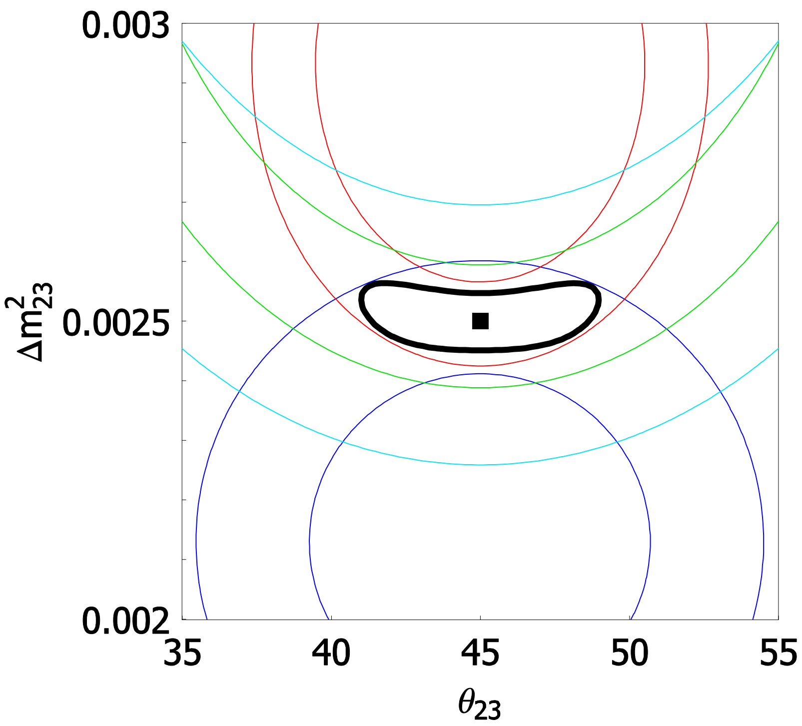
Energy Resolution



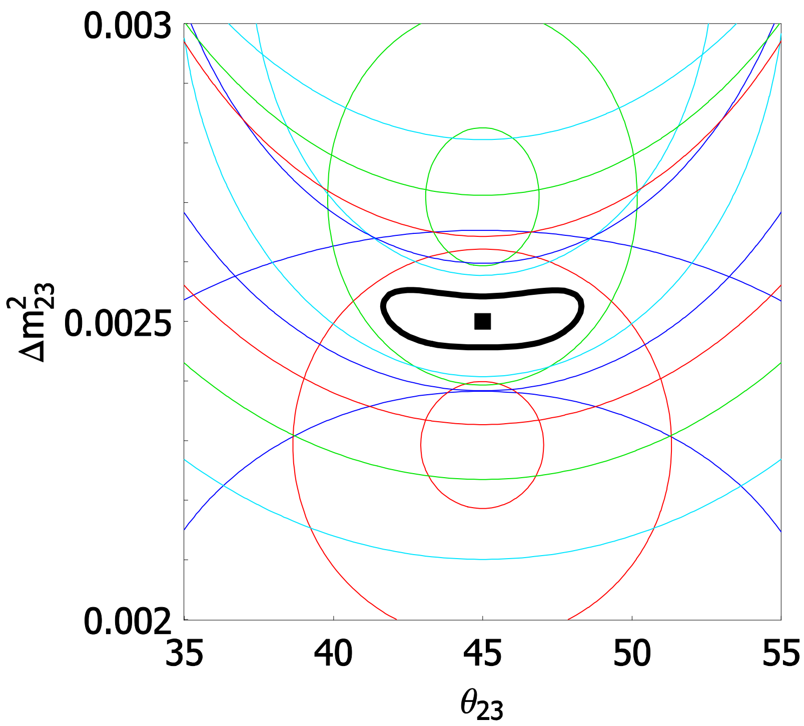
Red histogram for true QE events

Figure taken from
Y. Itow *et al.* hep-ex/0106019

Double energy resolution

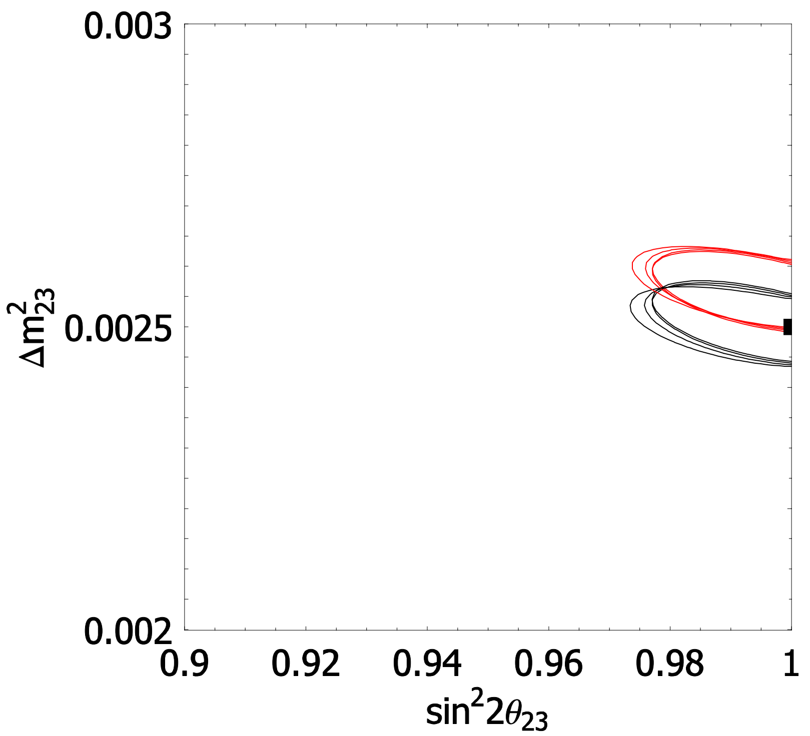


4 bins of 200MeV

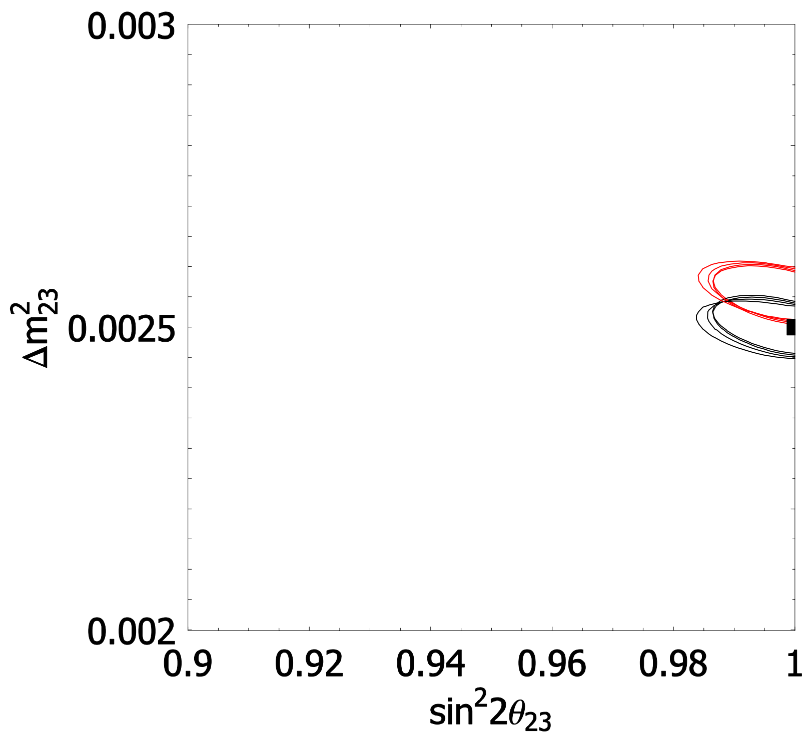


8 bins of 100MeV

Double energy resolution



4 bins of 200MeV



8 bins of 100MeV