Imperial College London

K. Long, 25 January, 2005

Neutrino Factory Physics

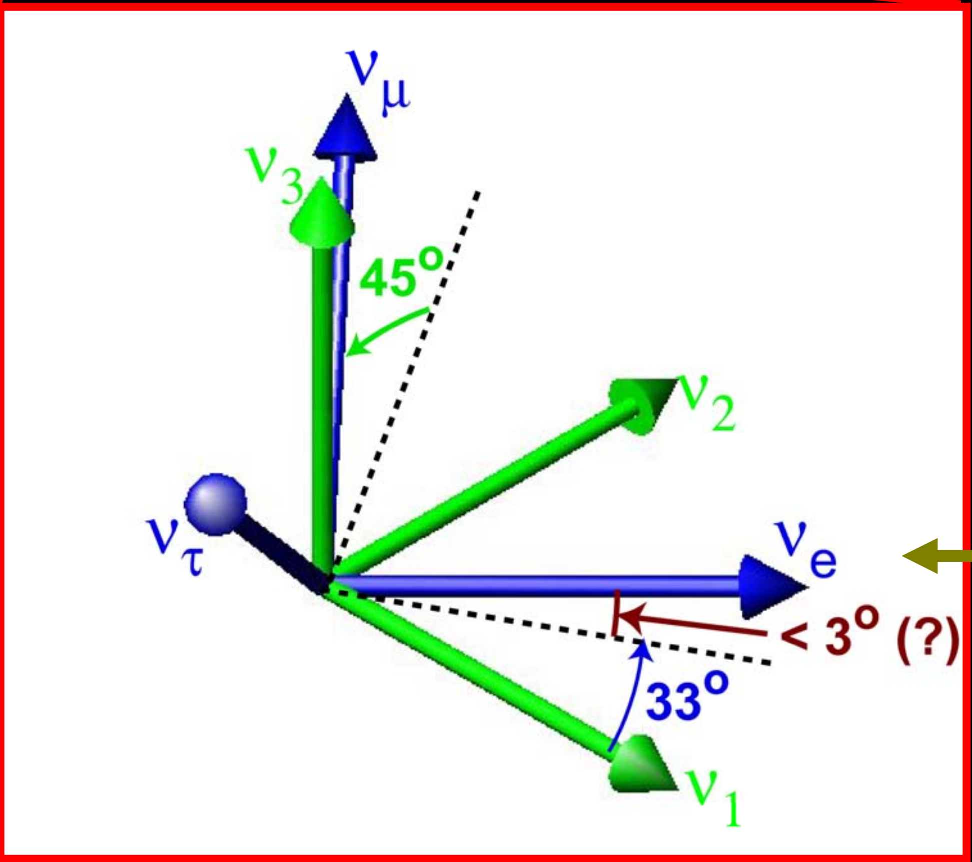
– headline tour

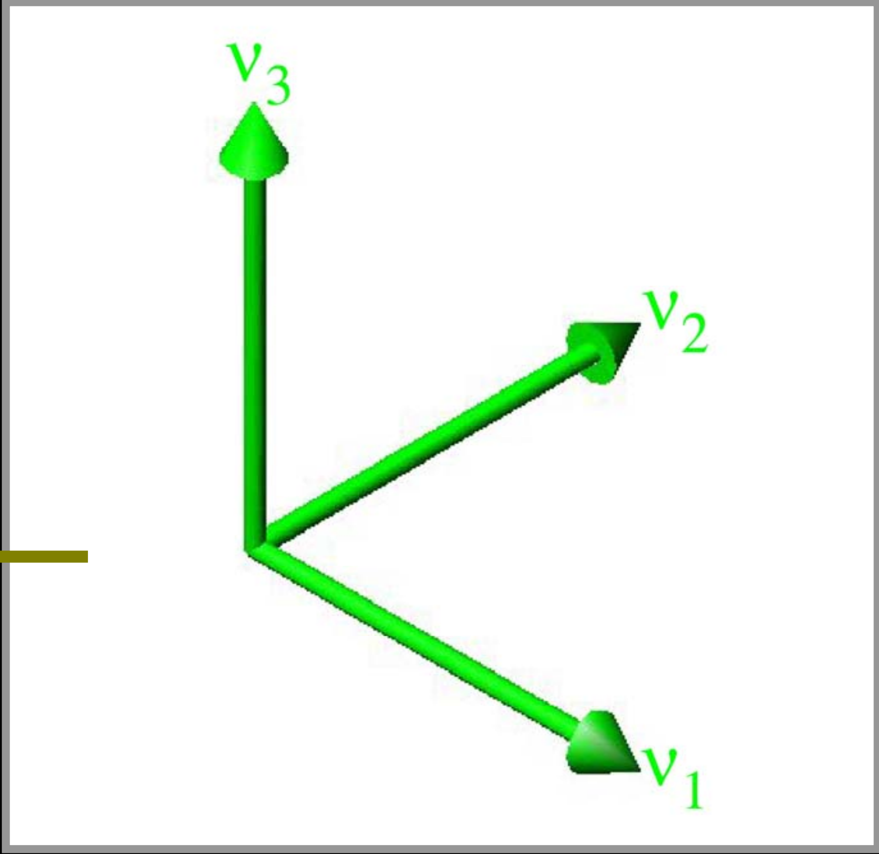
Contents

- Motivation
- Neutrino Factory concept
- Sensitivity
- Conclusions

Motivation: phenomenology

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

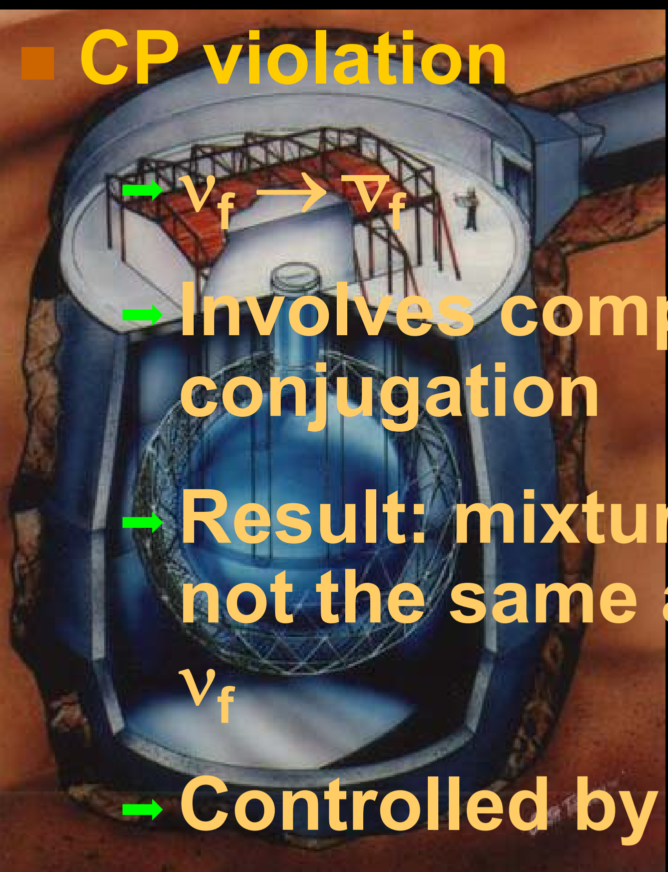


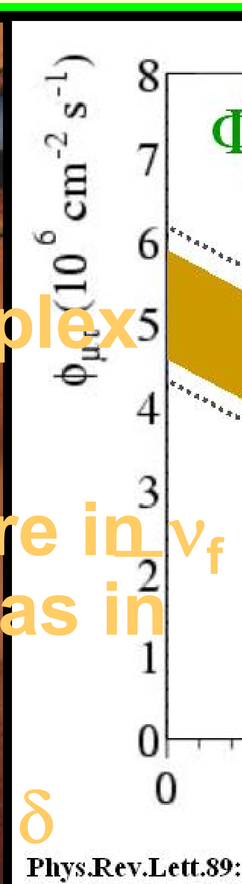


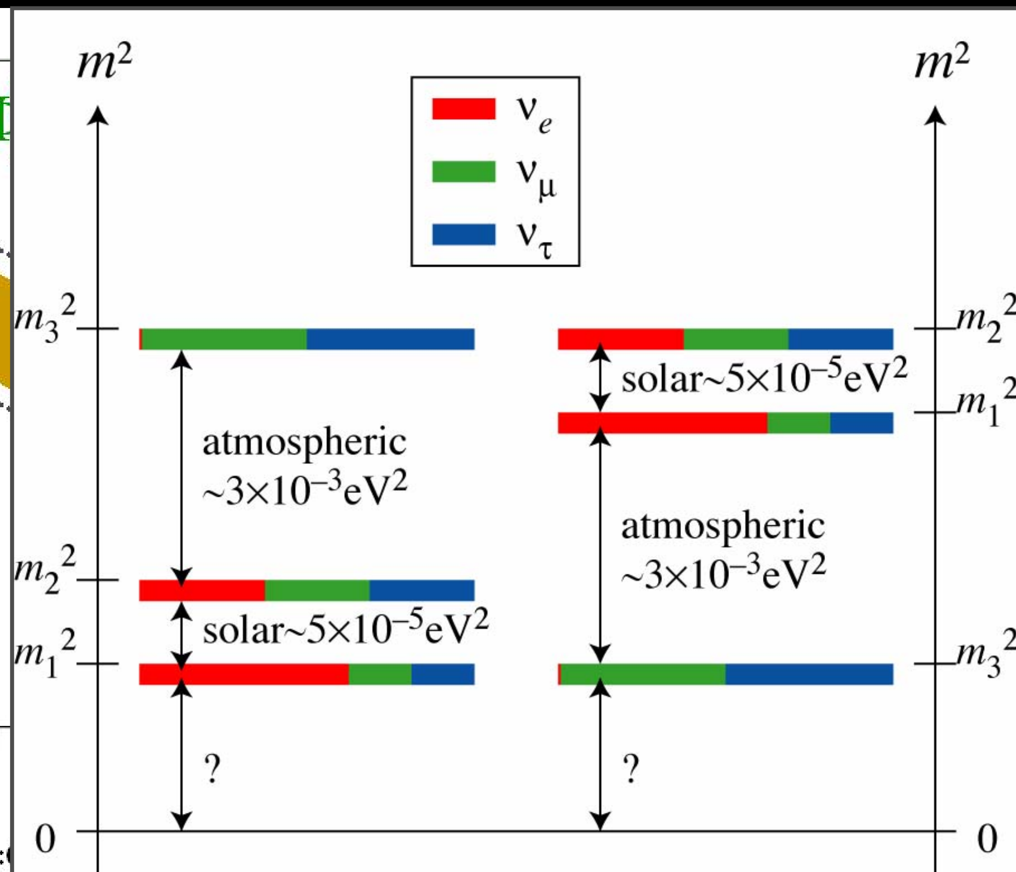
Motivation: phenomenology

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \quad \textbf{Solar} \quad \textbf{eric} \quad \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- CP violation
  - $\nu_f \rightarrow \bar{\nu}_f$
  - Involves complex conjugation
  - Result: mixture in ν_f not the same as in $\bar{\nu}_f$
  - Controlled by δ



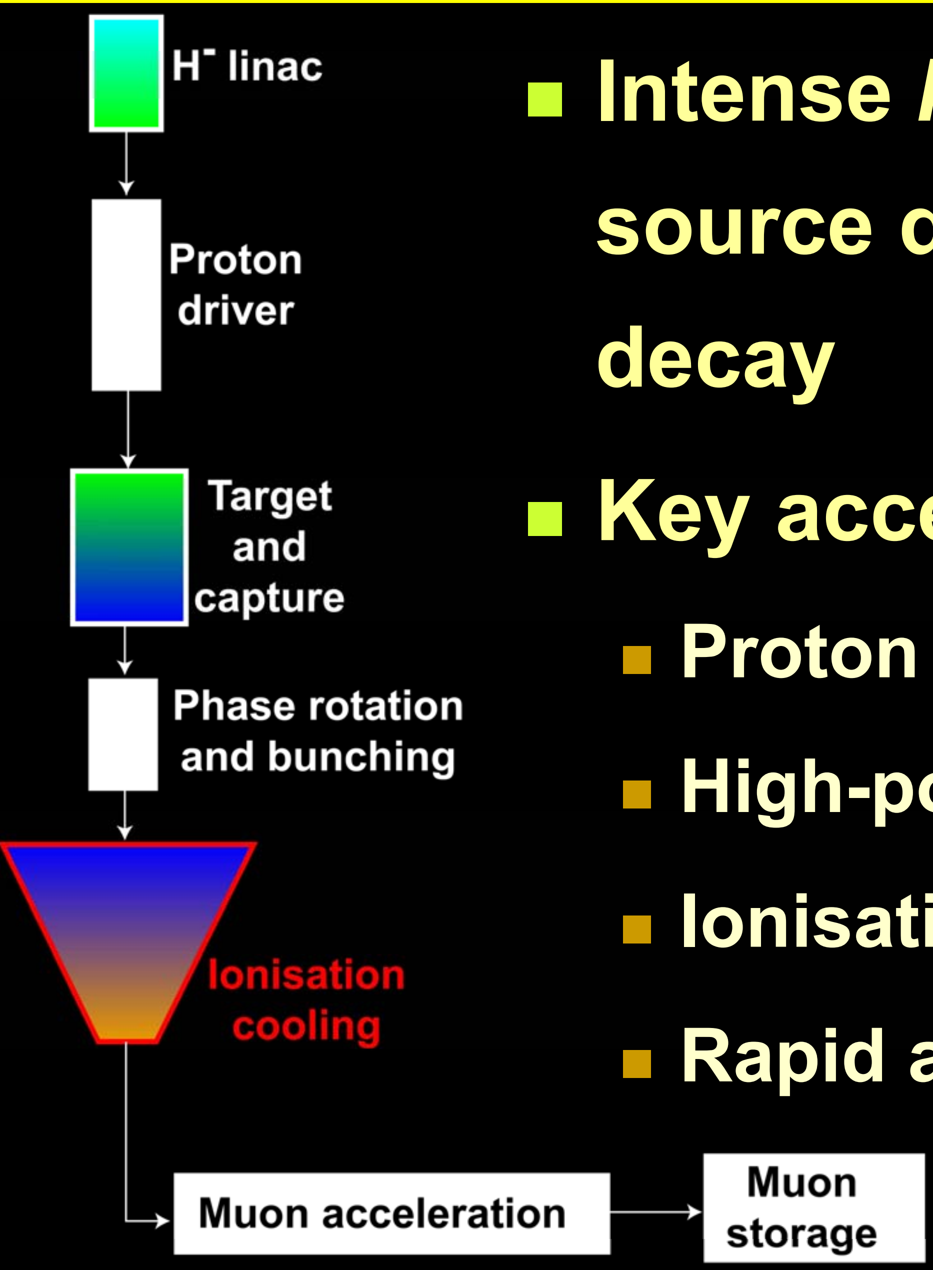




Motivation: parameters

- Mixing of three flavours of Dirac neutrino:
  - Three mixing angles: θ_{23}, θ_{12}, θ_{13}
  - CP phase: δ
  - Mass differences: Δm^2_{23}, Δm^2_{12}
- Two more CP phases for Majorana neutrino:
  - Oscillation insensitive to Majorana phases
- Neutrino Factory for *precision* neutrino measurements
  - Sign of Δm^2_{23}
  - Precision determination of θ_{13}
  - Search for non-zero δ

Neutrino Factory: concept



- Intense *high-energy* neutrino source derived from muon decay
- Key accelerator systems:
  - Proton driver
  - High-power target
  - Ionisation cooling
  - Rapid acceleration

Neutrino Factory: measurements

Δm^2_{23}	$\sin^2\theta_{13}$	δ

Neutrino Factory

- $\mu^- \rightarrow \nu_\mu + \nu_e$
- $\mu^+ \rightarrow \nu_\mu + \nu_e$

- High-energy
  - Require 'tracking' detector
  - Long (~n × 1000 km) baseline indicated

Features:

- Beam composition known
- Energy spectrum known
- Neutrino flux measured
- 1,000 times more intense than conventional beams

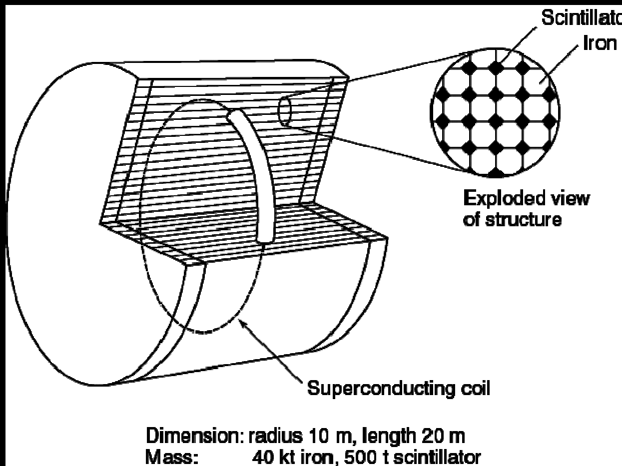
$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$	
Disappearance	**Appearance**
$\bar{\nu}_e \rightarrow \bar{\nu}_e \rightarrow e^+$	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$ $\bar{\nu}_e \rightarrow \bar{\nu}_\tau \rightarrow \tau^+$
$\nu_\mu \rightarrow \nu_\mu \rightarrow \mu^-$	$\nu_\mu \rightarrow \nu_e \rightarrow e^-$ $\nu_\mu \rightarrow \nu_\tau \rightarrow \tau^-$

Neutrino detection:

- Assume 'conservative' detector:
  - Fiducial mass: 50 – 100 kTon
  - Event classification:
    - Charged-current electrons/positrons
    - Right-sign muons (disappearance measurements)
    - Wrong-sign muons (appearance measurements)
    - Events with no leptons (neutral current)
- Example: magnetic calorimeters

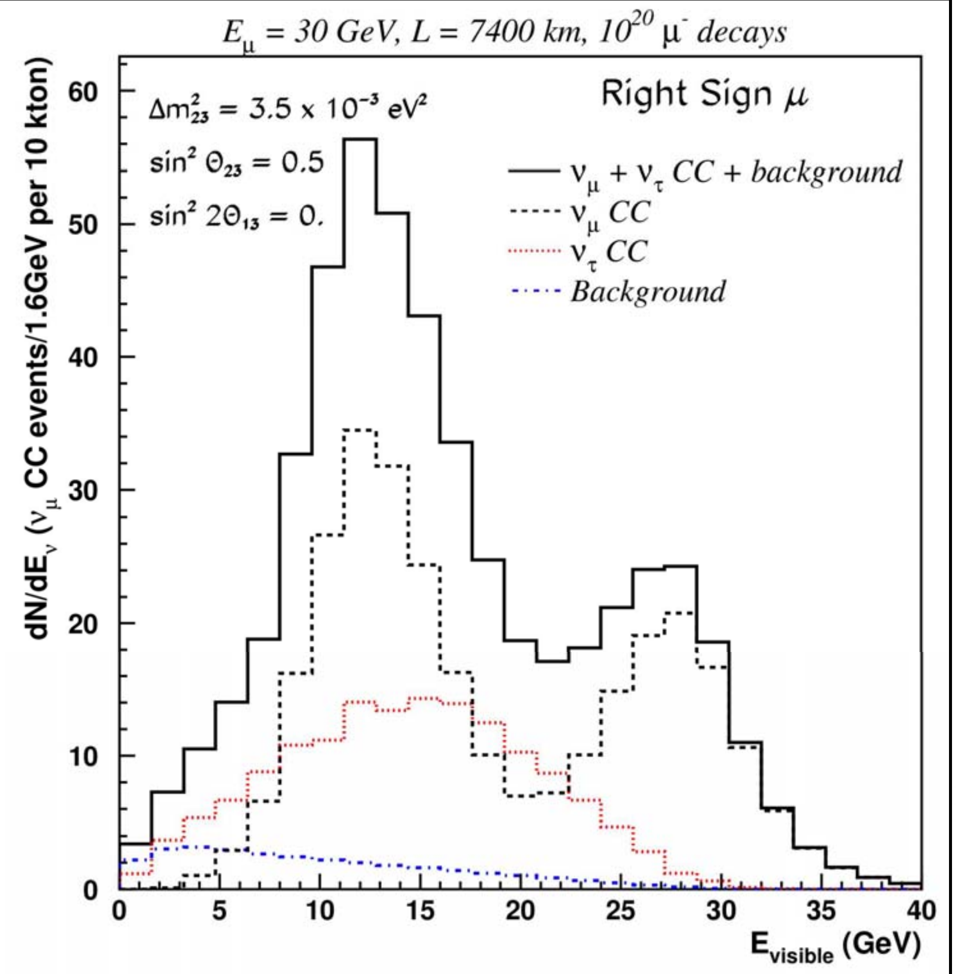
Monolith

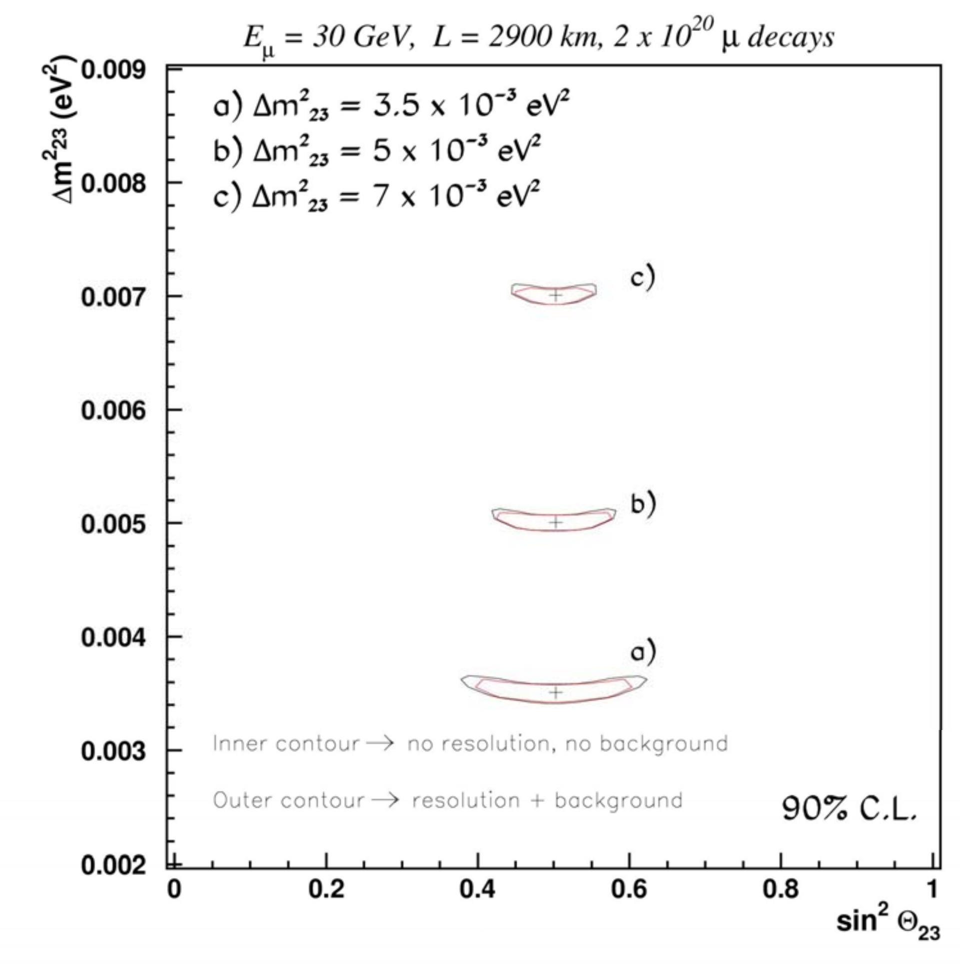
LMD



Δm^2_{23}	$\sin^2\theta_{13}$	δ

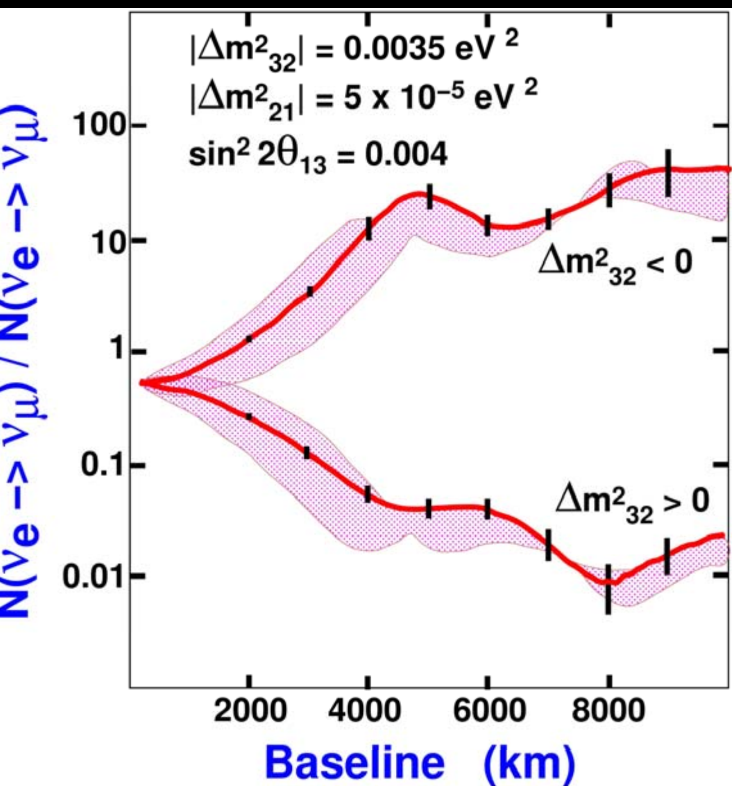
- **Right-sign muons: ν_μ disappearance**
- **Background at or below 1 in 10^{-5} – 10^{-4}**

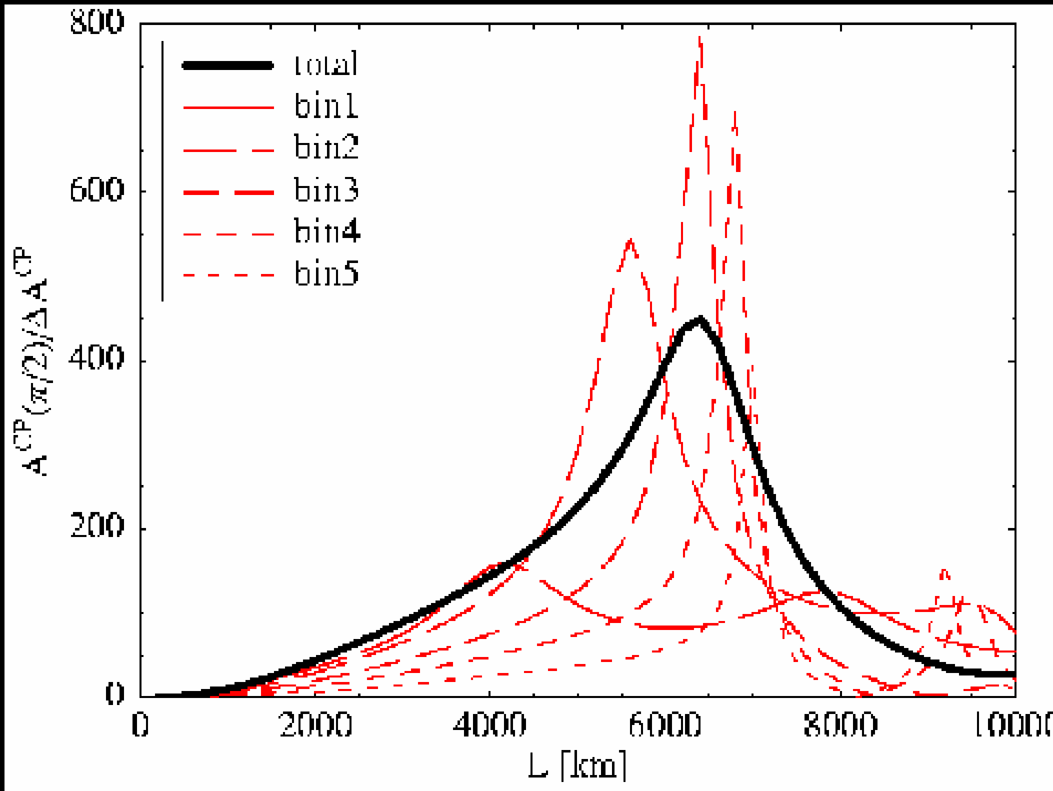




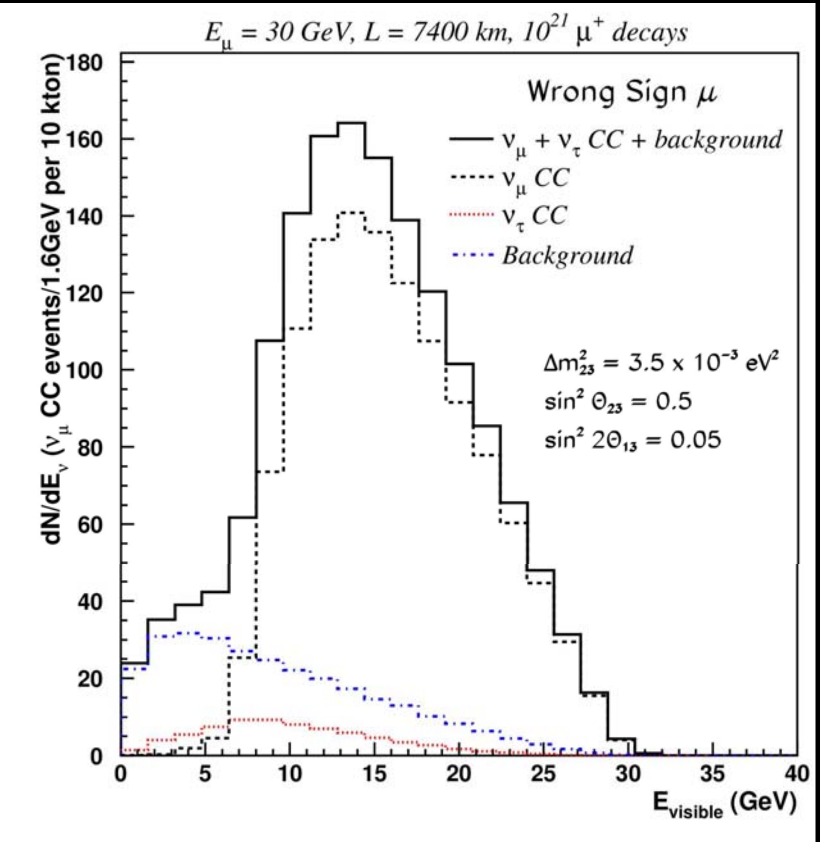
Δm^2_{23}	$\sin^2\theta_{13}$	δ

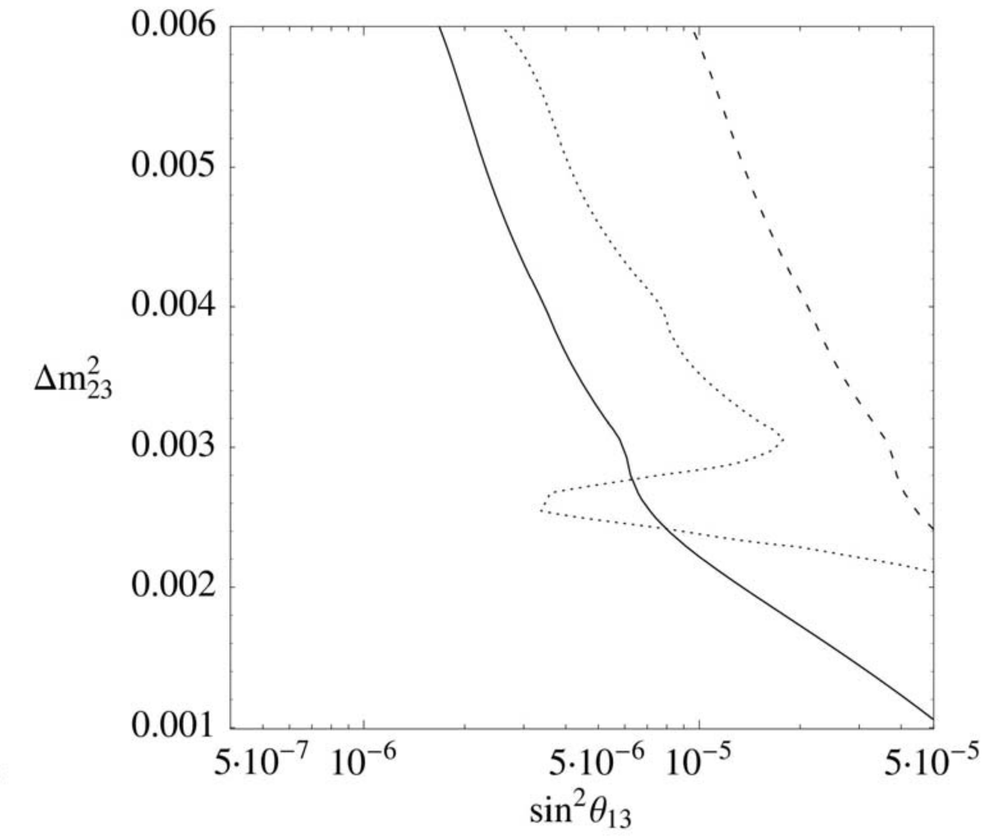
- **Measurement of sign of Δm^2_{23}**
  - Wrong-sign muon events: $\nu_e \rightarrow \nu_\mu$
  - Electron neutrino interactions with matter different from electron-antineutrino interactions
  - Requires baseline in excess of 1000 km





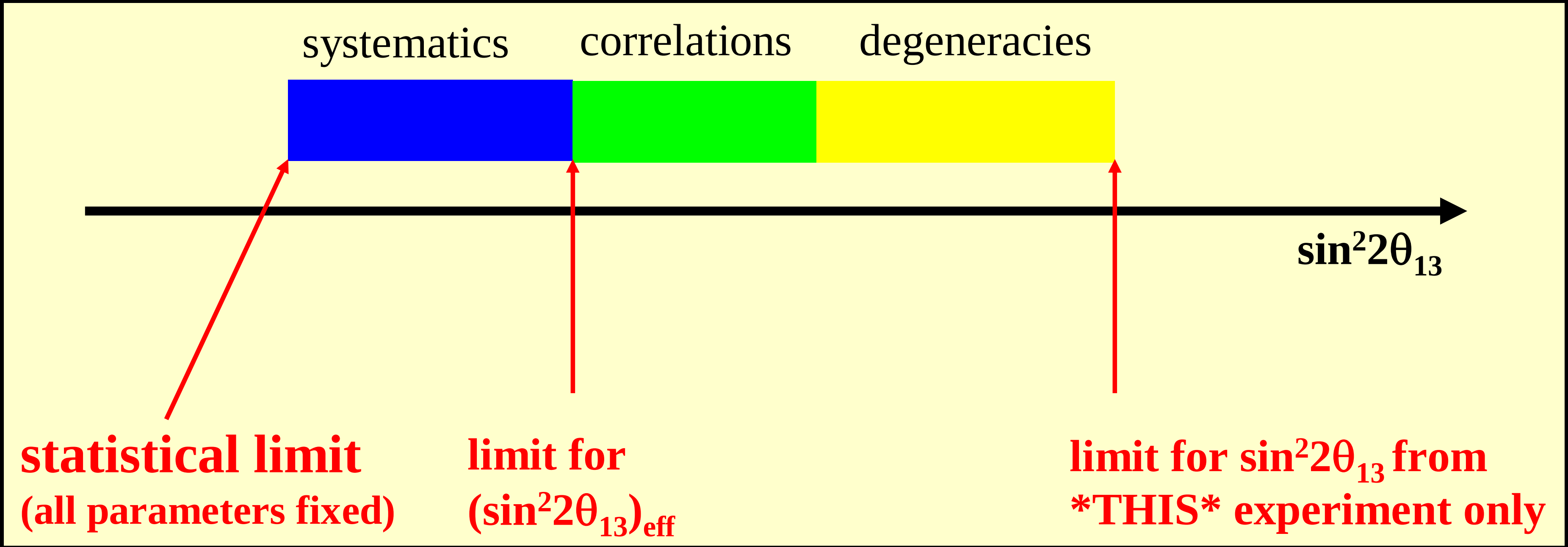
- θ_{13}: mixing of electron neutrinos with muon and tau neutrinos
  - Wrong-sign muon events: $\nu_e \rightarrow \nu_\mu$
  - Background at the level of $10^{-6} - 10^{-5}$



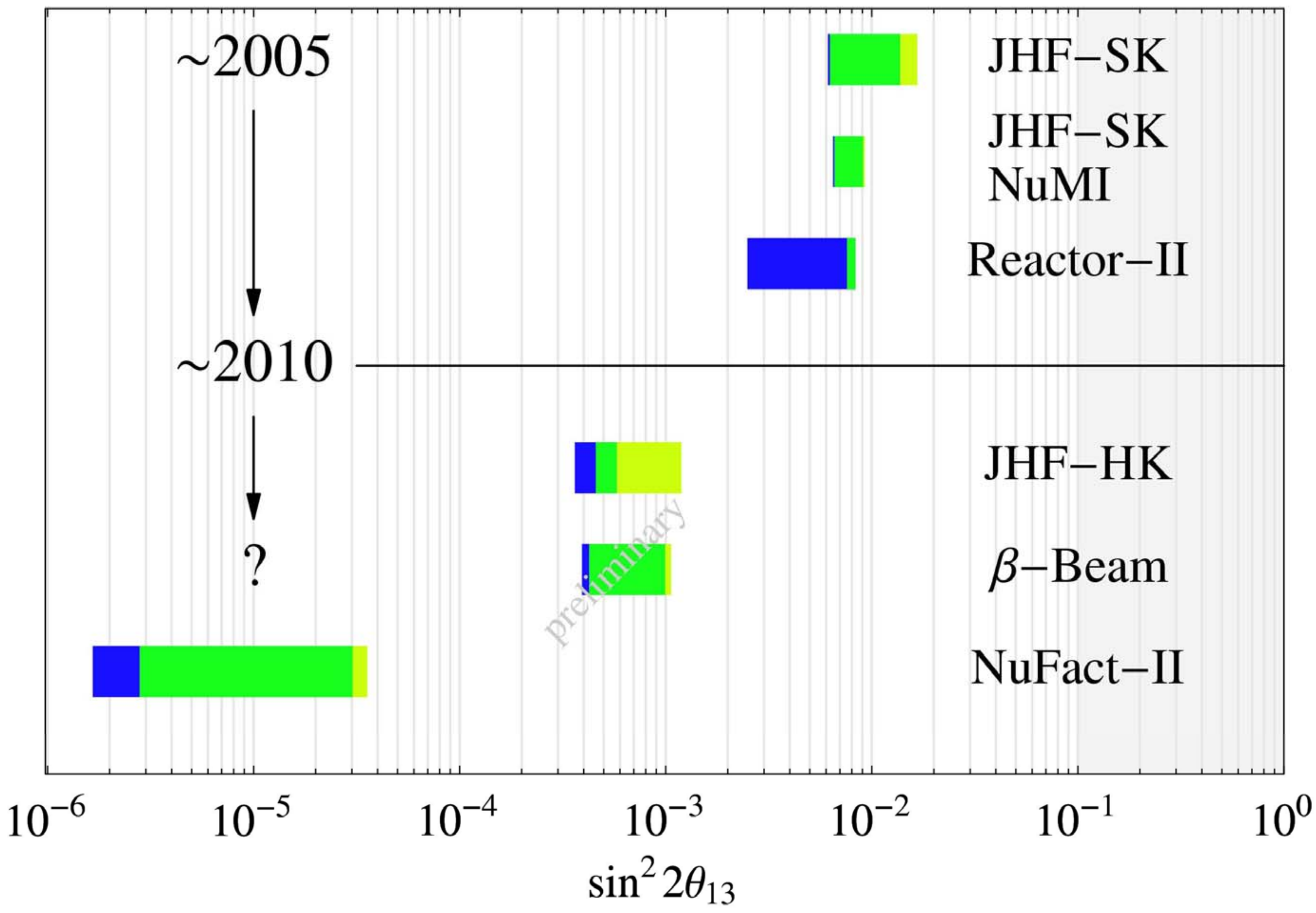


Δm^2_{23}	$\sin^2\theta_{13}$	δ

- Determine parameters from fit:
  - Include more than one data set
  - Several parameters are determined in fit
  - Leads to:
    - Correlations among the parameters
    - Degenerate solutions (same χ^2 for >1 solutions)



Δm^2_{23}	$\sin^2\theta_{13}$	δ

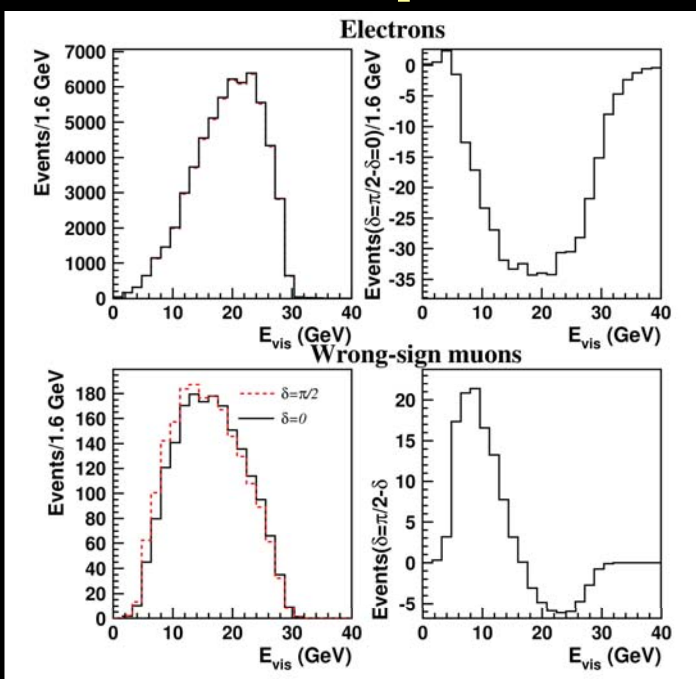


Δm^2_{23}	$\sin^2\theta_{13}$	δ

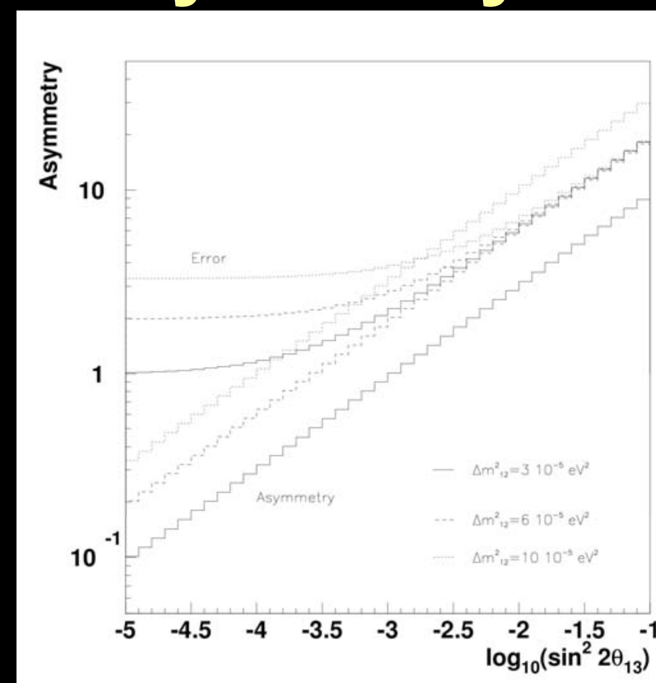
- **Measure asymmetry:**

$$A^{CP} = \frac{\left\{\frac{N(\mu^-)}{N_0(e^-)}\right\}_{\mu^-} - \left\{\frac{N(\mu^+)}{N_0(e^+)}\right\}_{\mu^-}}{\left\{\frac{N(\mu^-)}{N_0(e^-)}\right\}_{\mu^-} + \left\{\frac{N(\mu^+)}{N_0(e^+)}\right\}_{\mu^-}}$$

- **Data sample:**

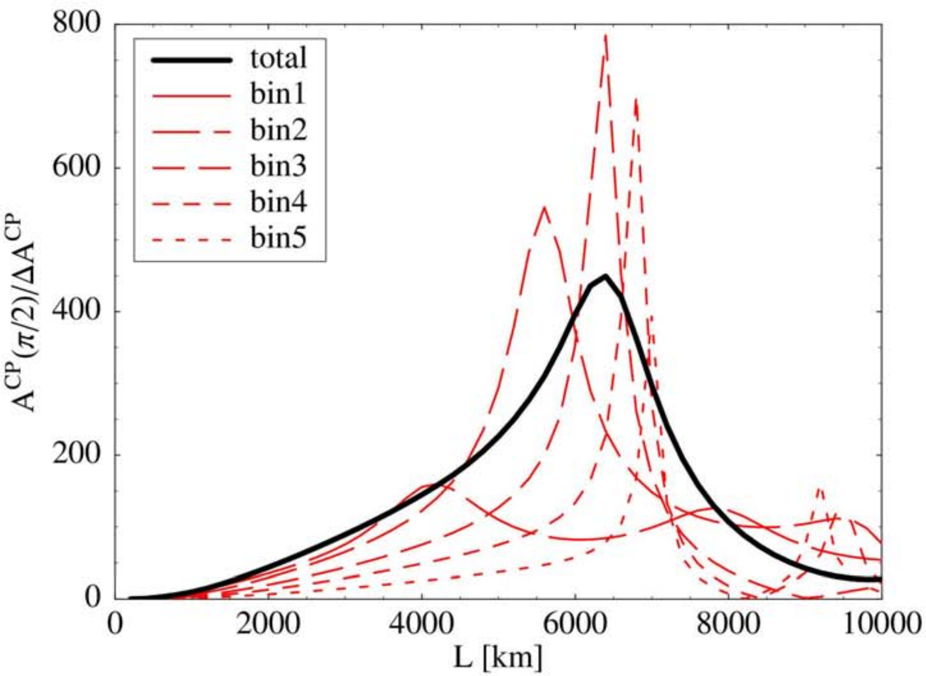


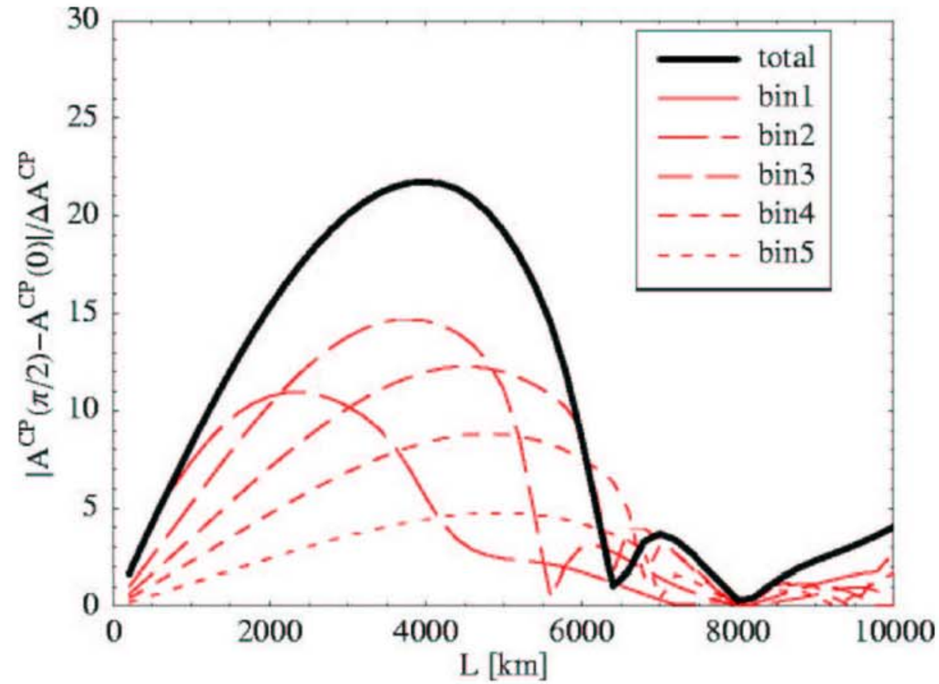
Asymmetry:



Δm^2_{23}	$\sin^2\theta_{13}$	δ

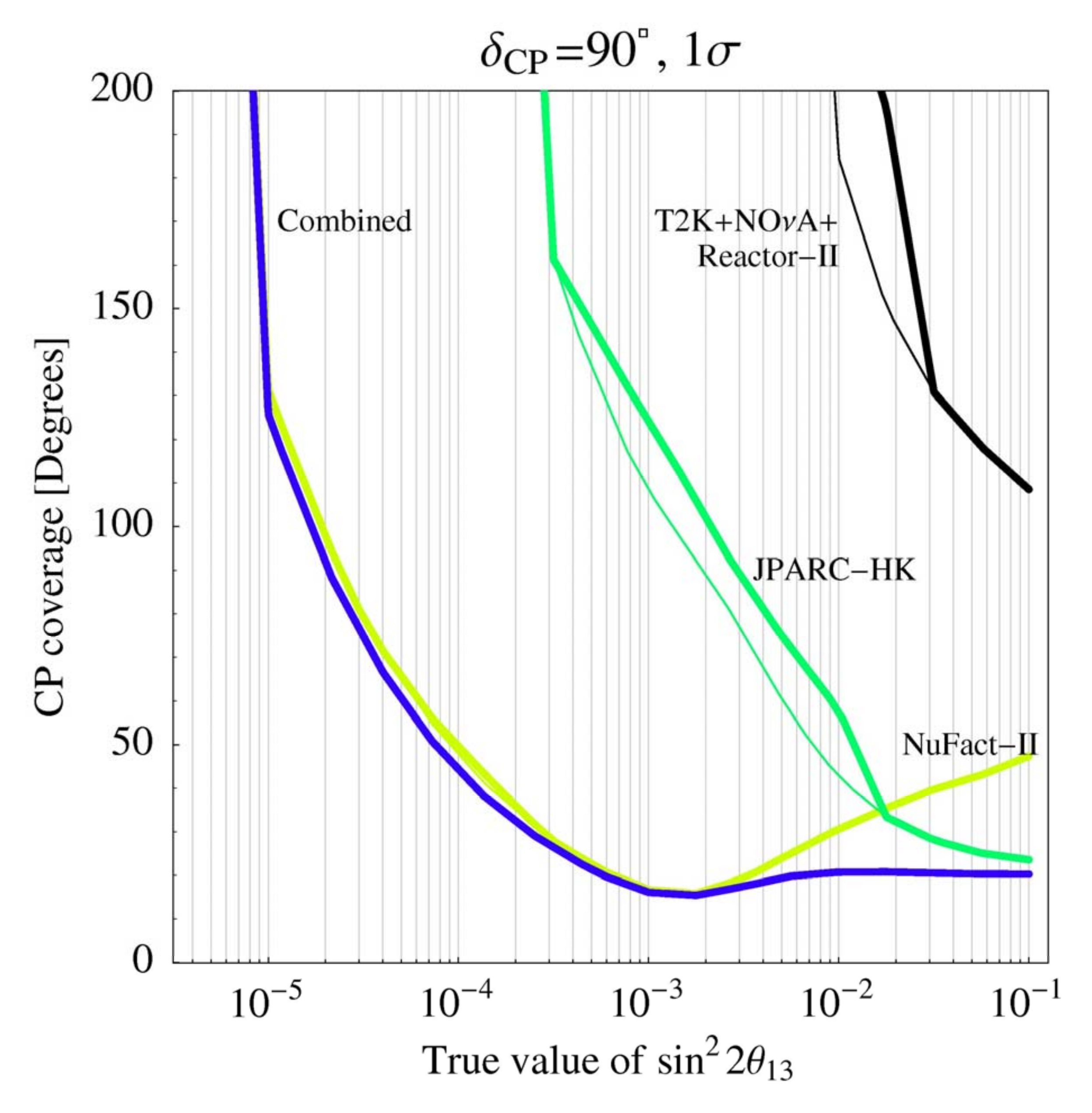
- CP asymmetry significance in the absence of ‘theoretical uncertainties’





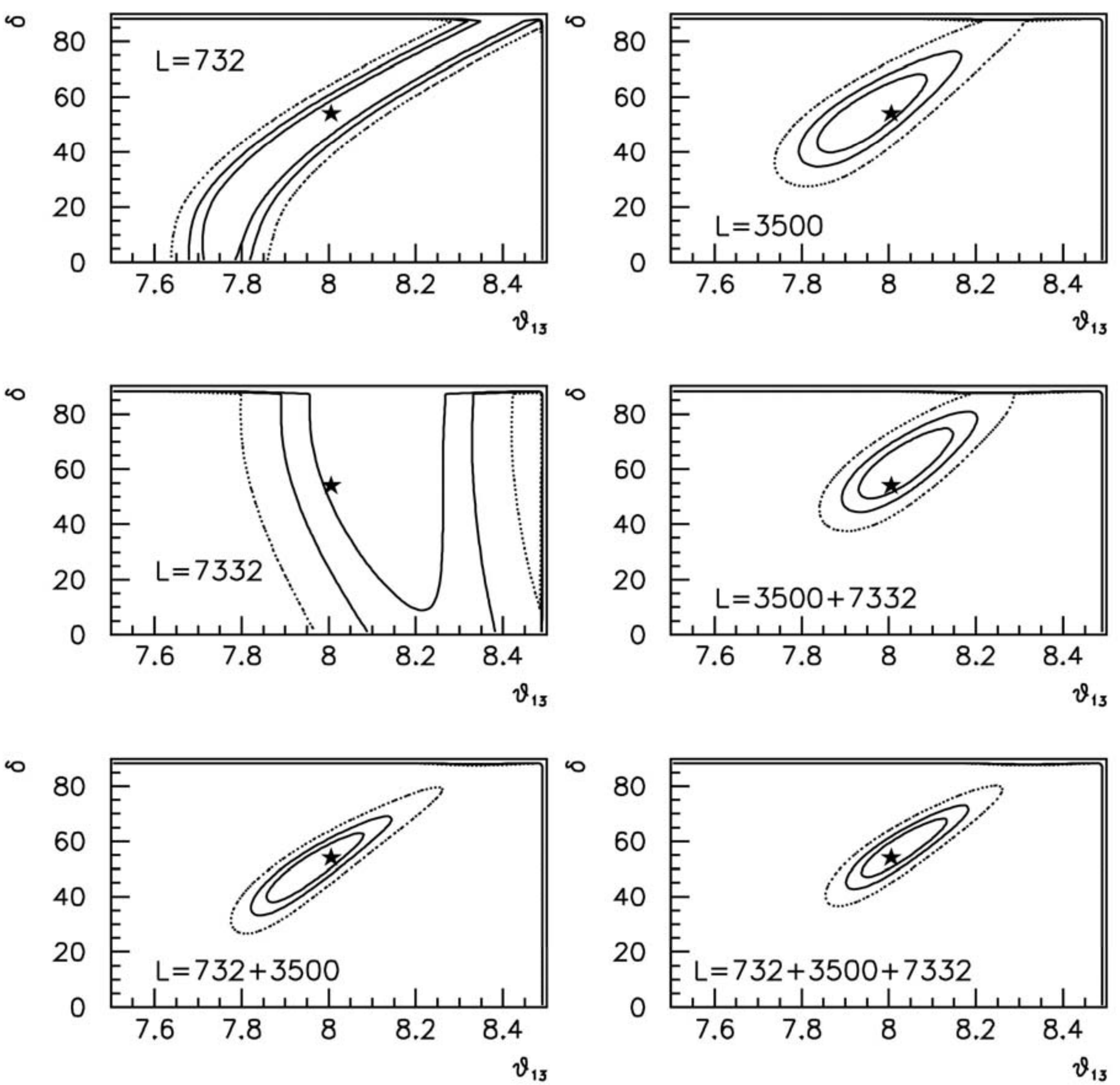
- Need to determine θ_{13}, δ simultaneously
  - Account for correlations and degeneracies

Δm^2_{23}	$\sin^2\theta_{13}$	δ



Δm^2_{23}	$\sin^2\theta_{13}$	δ

Neutrino Factory alone; multiple baselines:

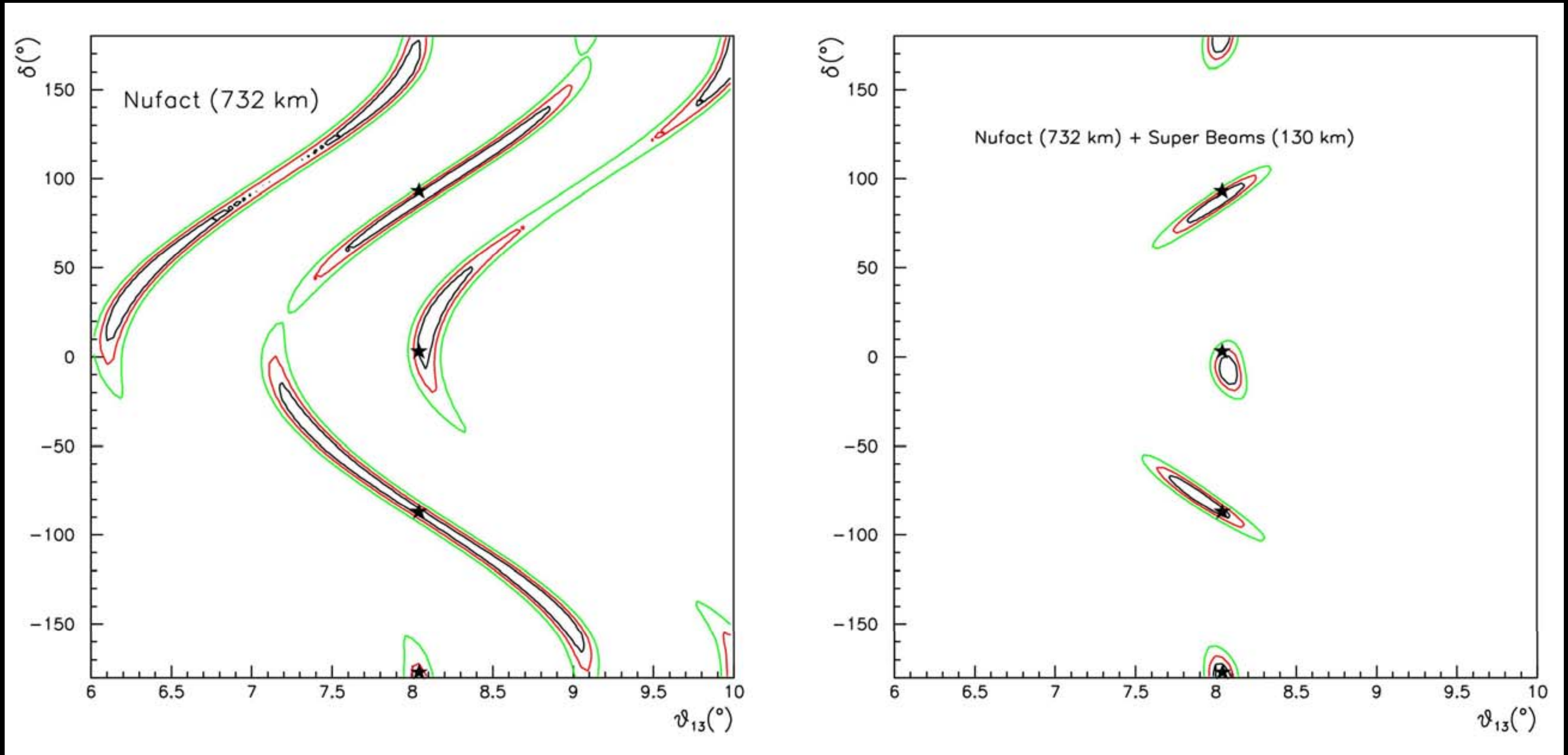


Trade off:

- **Sensitivity:**
  - **Minimum muon energy**
- **Background rejection**
  - **Muon energy cut**

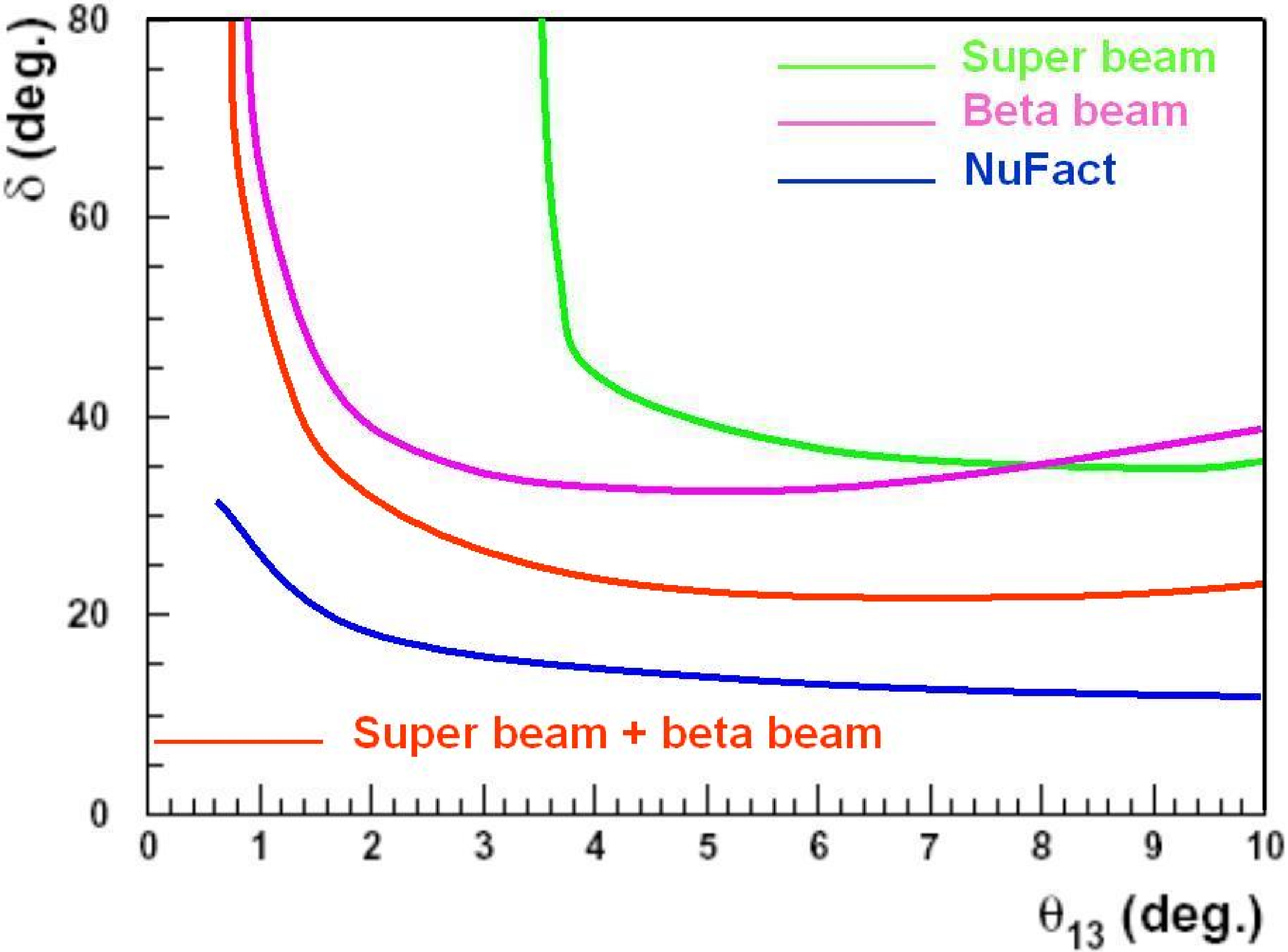
Δm^2_{23}	$\sin^2\theta_{13}$	δ

- **Degeneracy:**
  - Several classes:
    - Continuous parameters: θ_{13}, δ
    - Discrete parameters: sign(Δm^2_{23}), sign($\tan(2\theta_{23})$)
  - Include other channels or other experiments



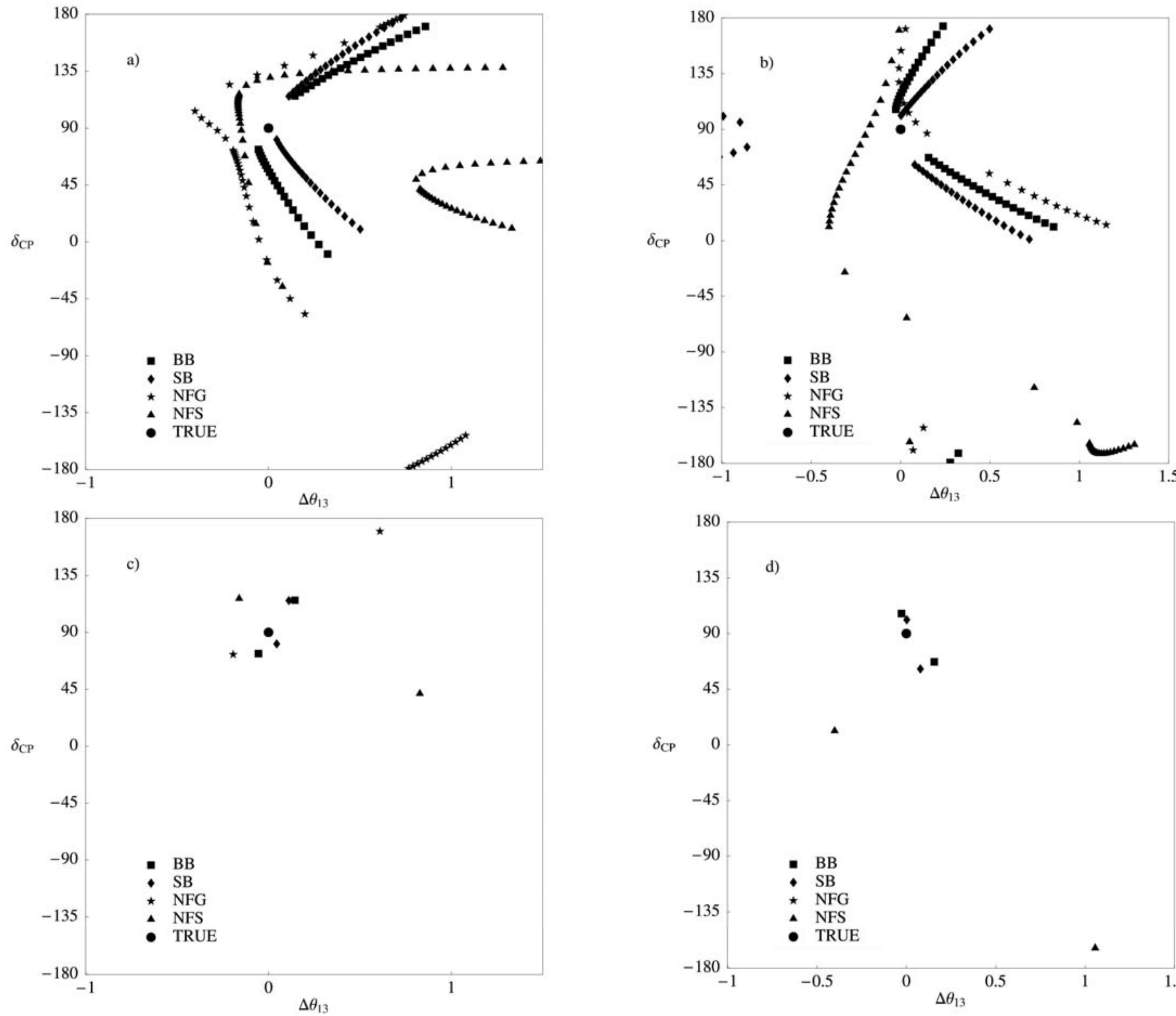
Δm^2_{23}	$\sin^2\theta_{13}$	δ

3 sigma sensitivity



Δm^2_{23}	$\sin^2\theta_{13}$	δ

- **Other channels:**
  - **Golden channel: wrong sign muons**
  - **Silver channel: tau appearance**
- **Other facilities:**
  - **Super beam**
  - **Beta beam**



Conclusions

- **Next generation super-beam experiments:**
  - **First measurement of θ_{13}**
- **Neutrino Factory allows:**
  - **Precise measurements of oscillation parameters**
  - **Most sensitive search for leptonic CP violation**
- **Neutrino Factory alone:**
  - **Measure θ_{13}; potential to discover $\delta \neq 0$**
  - **Can not resolve all degeneracies**
    - **Requires super beam or beta beam**
- **Need for design studies:**
  - **Need to understand sensitivities and limitations of each facility on equal footing**
  - **Need to compare performance and cost**
  - **Need for robust design studies of:**
    - **Beta beam**
    - **Neutrino Factory**

  So allow a consensus plan for an exciting future to emerge