Optimization studies for CP violation

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Neutrino masses and mixings

Les Houches, June 2001

Layout

- Oscillation probability for complex mixing
- Fluxes in a Neutrino Factory
- Scaled probabilities
- Correlation CP-θ_{13}
- Matter propagation
- L/E_ν scaling
- Determination of oscillation probabilities
- Electron charge
- T-violation
- Conclusions

Introduction

Optimizing the search for a complex phase in the leptonic mixing matrix far from trivial

- A priori, the effect depends on L and E in a complicated way (In vacuum, the scaling of the effect with L/E can help an intuitive understanding of the oscillation behavior)

- Measurement precision depends on practical limits on machine power, maximal energy/flux, detector mass

The choice of the baseline is critical: at the time of the Neutrino Factory, there will be already experiments located at a distance of 250 km from JHF and 730 km from CERN and FNAL; if new sites are really needed, due to physics considerations, that would require major new investments

$\nu_e \rightarrow \nu_\mu$ oscillation probability

Following the conventional formalism for leptonic mixing, CP-violating effects are observed in appearance transitions involving the first family. Experimentally, $\nu_\mu \rightarrow \nu_e$ is clearly favored.

This probability is composed of three terms:

Independent of δ

$$P(\nu_e \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) =$$

$$4c^2_{13}[\sin^2 \Delta_{23} s^2_{12} s^2_{13} + c^2_{12}(\sin^2\Delta_{13} s^2_{13} s^2_{23} + \sin^2\Delta_{12} s^2_{12}(1-(1+s^2_{13})s^2_{23}))]$$

$$-1/2c^2_{13}\sin^2\theta_{12} s_{13} \sin^2\theta_{23} \cos\delta[\cos^2\Delta_{13} - \cos^2\Delta_{23} - 2\cos^2\theta_{12}\sin^2\Delta_{12}]$$

CP-even

$$+1/2c^2_{13}\sin\delta \sin 2\theta_{12} s_{13} \sin^2\theta_{23}[\sin^2\Delta_{12} - \sin^2\Delta_{13} + \sin^2\Delta_{23}]$$

CP-odd

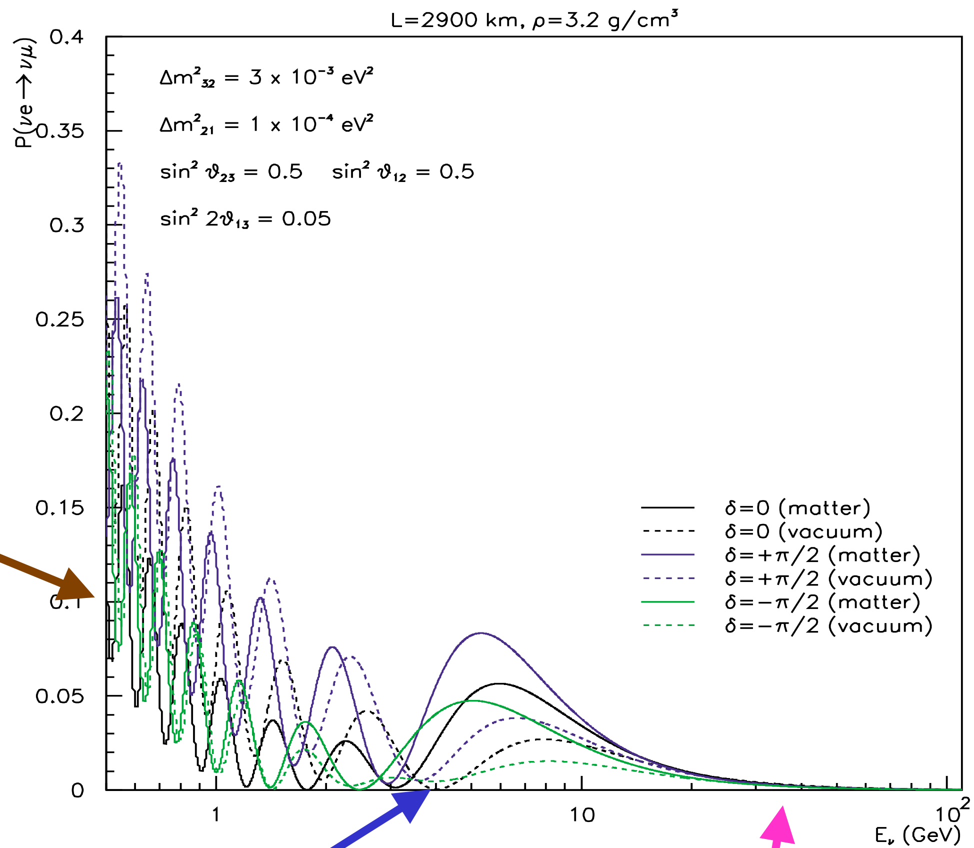
L/E regimes

$\Delta m^2_{21}\,(L/4E_\nu)>1$

&

$\Delta m^2_{32}\,(L/4E_\nu)>1$

⇒L/E of solar



$\Delta m^2_{21}\,(L/4E_\nu)<<1$

&

$\Delta m^2_{32}\,(L/4E_\nu)>1$

⇒L/E of atmospherics

$f\times\Delta m^2_{12}\,(L/4E_\nu)\times\sin^2(\Delta m^2_{23}\,L/4E_\nu)$

$\Delta m^2_{21}\,(L/4E_\nu)<<1$

&

$\Delta m^2_{32}\,(L/4E_\nu)<<1$

$f\times\Delta m^2_{12}\,(\Delta m^2_{23})^2(L/4E_\nu)^3$

Observable quantities

• $\Delta\delta \equiv P(\nu_e \rightarrow \nu_\mu; \delta=\pi/2) - P(\nu_e \rightarrow \nu_\mu; \delta=0)$

Compares oscillation probabilities as a function of E_ν measured with wrong-sign muon event spectra, to MonteCarlo predictions of the spectrum in absence of CP violation

• $\Delta CP(\delta) \equiv P(\nu_e \rightarrow \nu_\mu; \delta) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu; \delta)$

Compares oscillation probabilities measured using the appearance of ν_μ and $\bar{\nu}_\mu$, running the storage ring with a beam of stored μ^+ and μ^-, respectively. Matter effects are dominant at large distances

• $\Delta T(\delta) \equiv P(\nu_e \rightarrow \nu_\mu; \delta) - P(\nu_\mu \rightarrow \nu_e; \delta)$

Compares the appearance of ν_μ and ν_e in a beam of stored μ^+ and μ^-. As opposite to the previous case, matter effects are the same, thus cancel out in the difference

• $\Delta \bar{T}(\delta) \equiv P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu; \delta) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e; \delta)$

Same as previous case, but with antineutrinos. This effect is usually matter-suppressed with respect to the neutrino case.

Measuring ΔT

The comparison of $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\mu$ oscillation probabilities offers a direct way to highlight a complex component in the mixing matrix, independent of matter and other oscillation parameters.

This measurement is not directly accessible at a Neutrino Factory with a conventional detector due to the large ν_e background in the beam. It would add a considerable improvement to the physics reach of a Neutrino Factory

Two methods have been proposed to solve the problem of beam ν_e background :

- Beam polarization (not very effective; see A.Blondel, A.Bueno, M.Campanelli, A.Rubbia, Monterey proceedings)
- Electron charge (discussed later in this talk)

Oscillation probabilities

For a complex mixing matrix (in vacuum)

$\Delta CP = \Delta T =$

□
1

Complex term in matrix

Need LA MSW

Oscillation P goes like $\sin^2\theta_{13}$
hence, $\Delta CP/$□P independent of θ_{13}

$$2 \cos\theta_{13} \sin\delta \sin2\theta_{12} \sin2\theta_{13} \sin2\theta_{23} \times \sin(\Delta m^2_{12} L/4E_\nu) \sin(\Delta m^2_{13} L/4E_\nu) \sin(\Delta m^2_{23} L/4E_\nu)$$

Oscillating term only depends on L/E

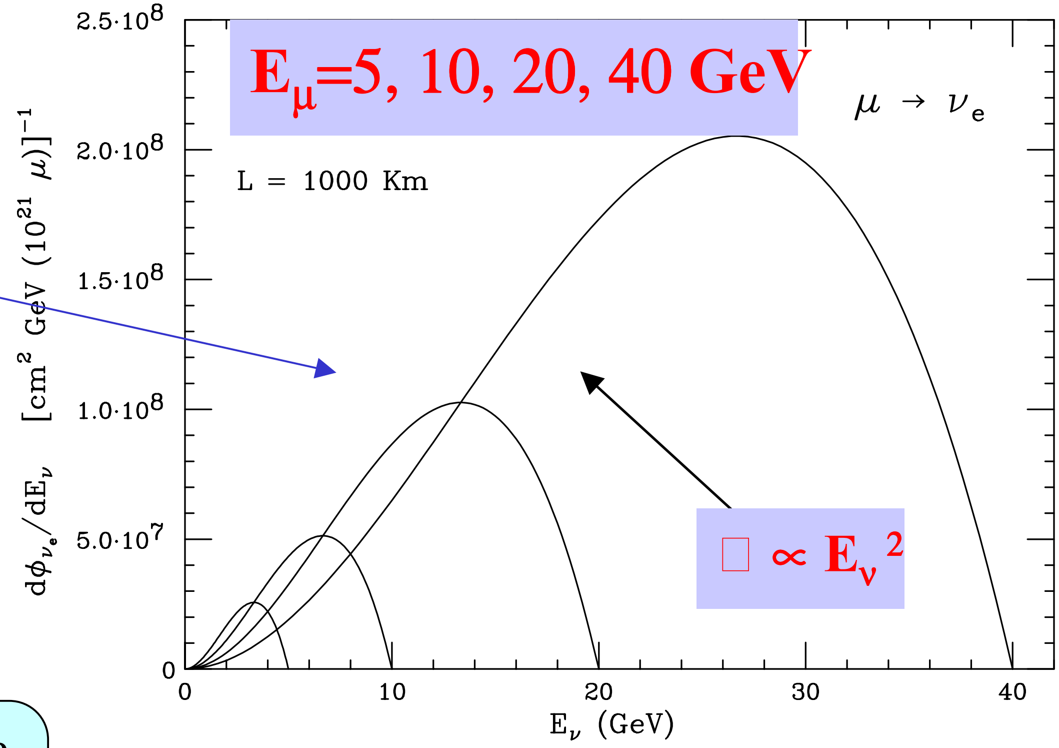
Neutrino Factory fluxes

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu \quad or \quad \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

P. Lipari, hep-ph/0102046

Forward neutrino spectrum fixed by μ decay kinematics

Only scales with energy



Integrating:

Flux scales as E^2_μ/L^2

Total event rate scales as $\square E^3_\mu/L^2$

$$\frac{dN}{dx} \propto x^2(1-x) \qquad x \equiv E_\nu / E_\mu$$

Scaled probabilities

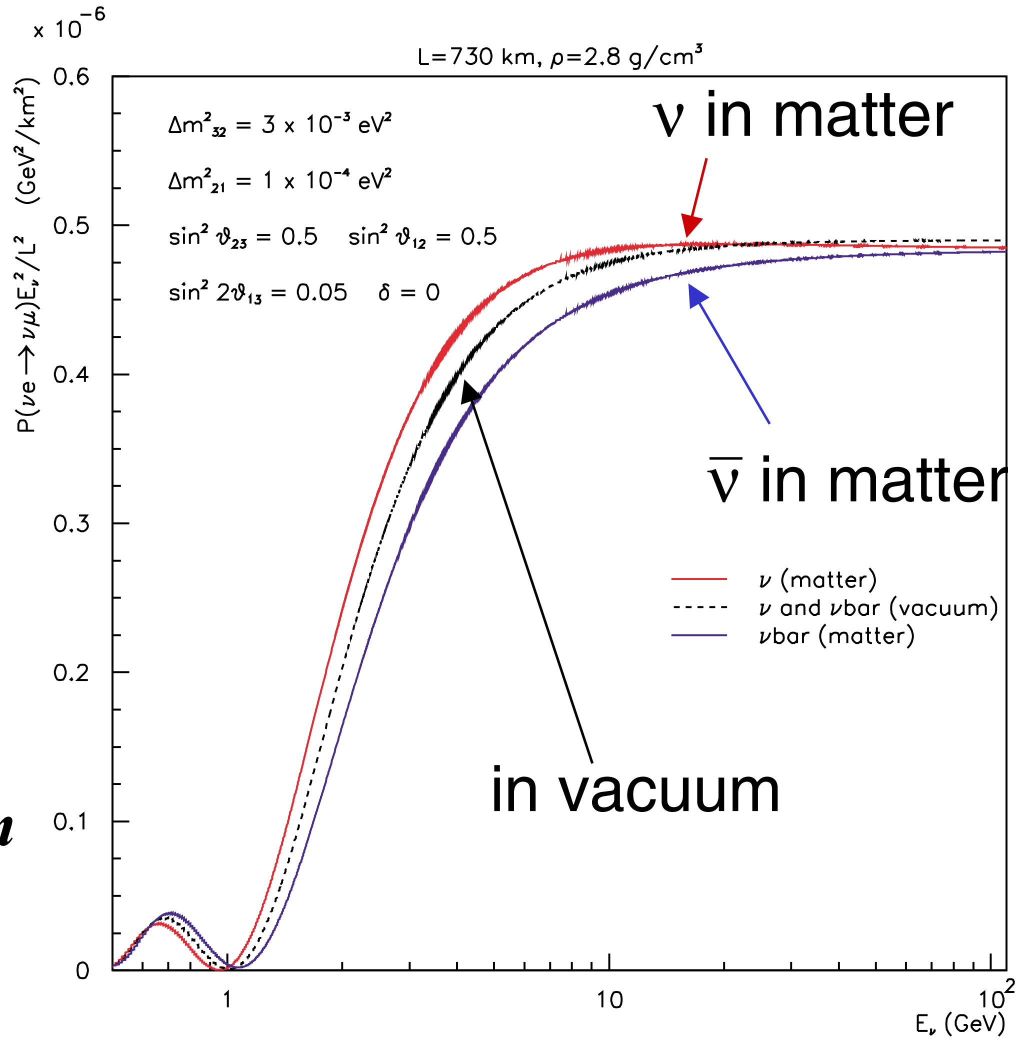
We define:

$$p \equiv P(\nu_e \to \nu_\mu) \times E_\nu^2 / L^2$$

probability

Approximate E_ν-dependence of NF ν-spectrum

Flux attentuation with distance



1. p→const when $E_\nu \to \infty$

2. It ***correctly "weighs" the probabilities with the E_ν dependence of the NF ν spectrum***

3. p can be ***directly compared at different baselines***

E_ν

CP violation at high energy?

See also P. Lipari, hep-ph/0102046

L=730 km

$$P(\nu_e \rightarrow \nu_\mu) \times E_\nu^2 / L^2$$

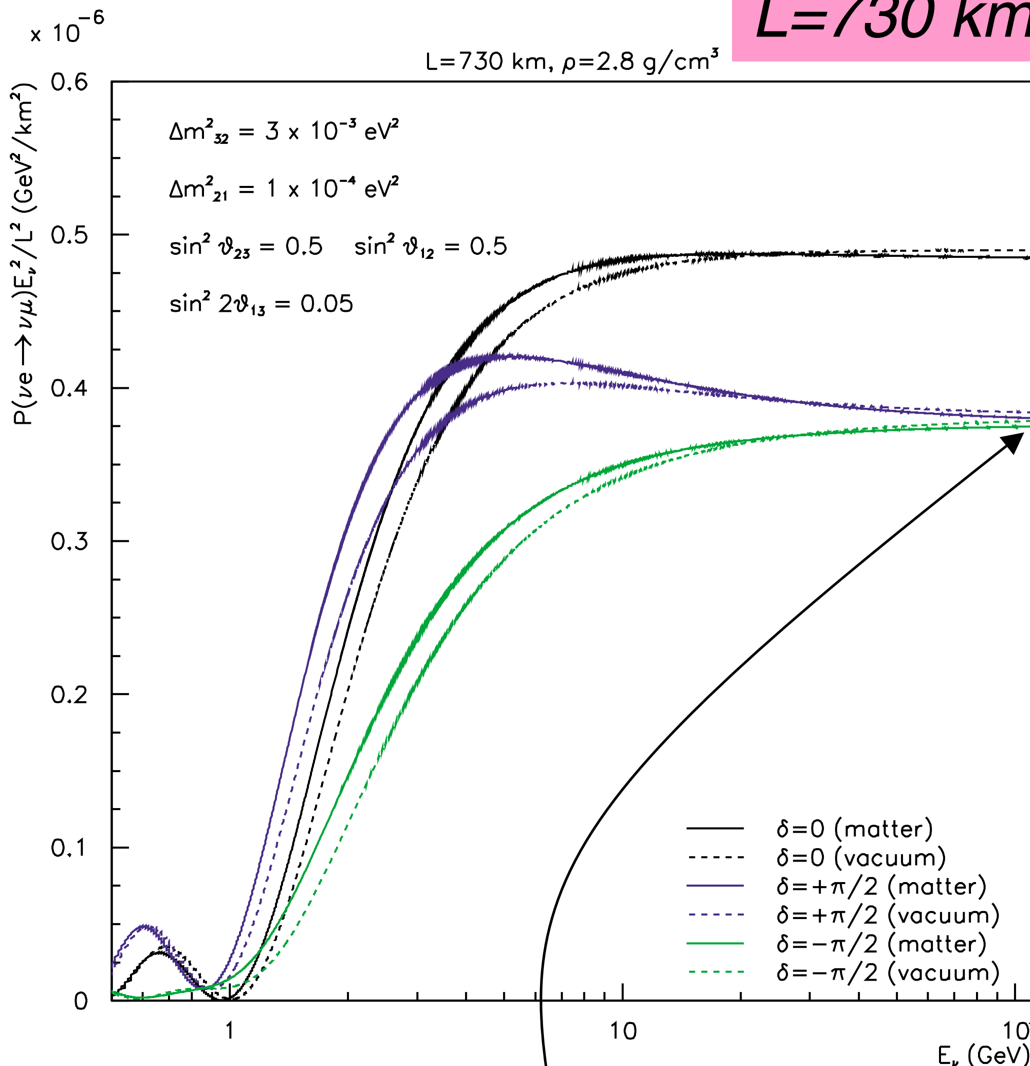
1. The E_ν^2 term takes into account that the NF likes to go to high energy

$\Rightarrow$ damps the part Δm^2_{21} (L/4E_ν)≈1

2. At "high energy", i.e. Δm^2_{21} (L/4E_ν)<<1 & Δm^2_{32} (L/4E_ν)<<1, there is no more oscillation

$\Rightarrow$ change of δ = change of θ_{13} !!!

3. At "high energy", the CP-effect goes like cosδ, as pointed out by Lipari $\Rightarrow$ cannot measure sign of δ



$$P\left(\nu_e \rightarrow \nu_\mu, \delta = \frac{\pi}{2}\right) - P\left(\nu_e \rightarrow \nu_\mu, \delta = 0\right) \propto \cos\delta$$

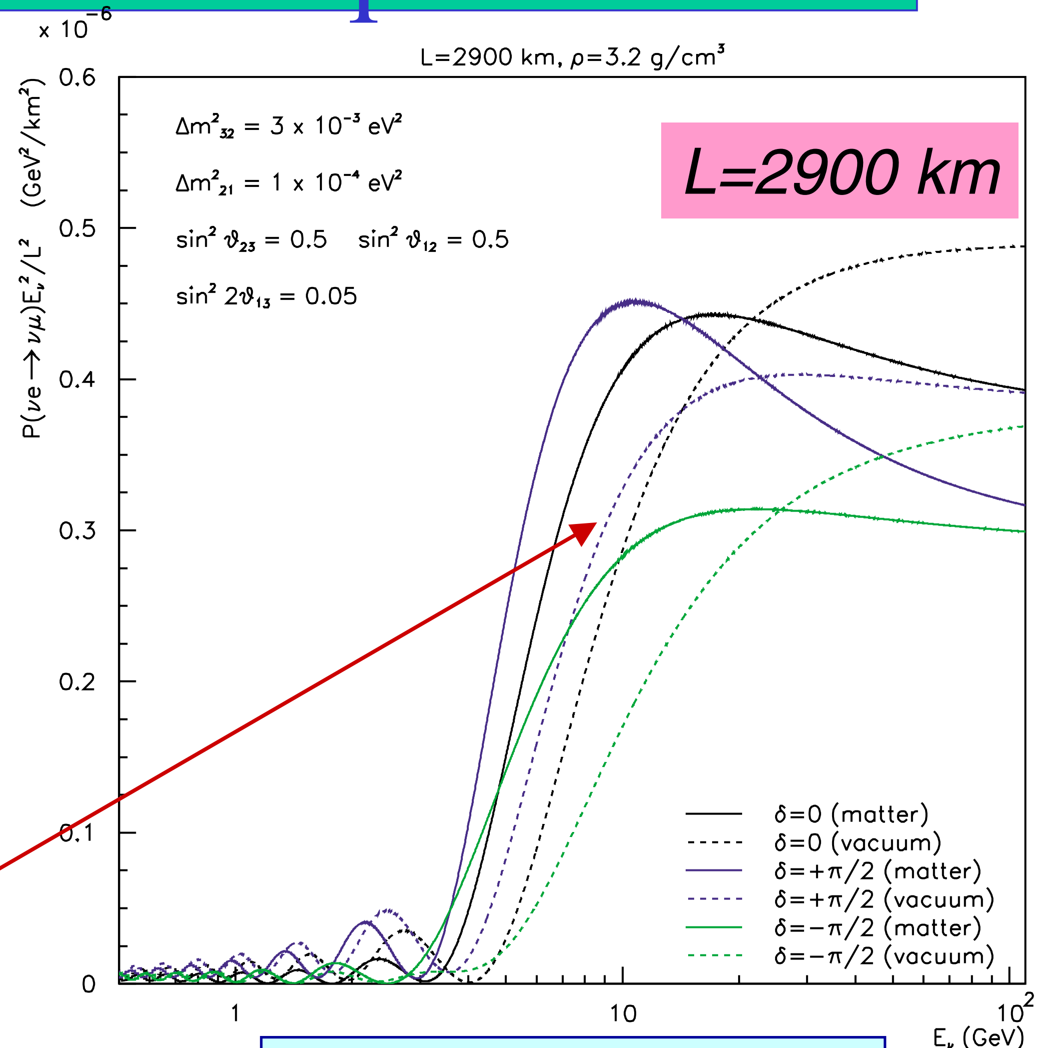
Looking for a compromise

We must compromise at "medium" energy to

1. This means $\Delta m^2_{21}(L/4E_\nu) \ll 1$ & $\Delta m^2_{32}(L/4E_\nu) \approx 1$

2. To gain from the E_μ^3 behavior of the NF

3. To guarantee the possibility to disentangle δ from θ_{13}



Position of first maximum!

$$\frac{L}{E_\nu} \approx \frac{4\pi}{2\Delta m^2_{32}}$$

- $E_{\nu,MAX}$ □ 2 GeV for L=732 km
- $E_{\nu,MAX}$ □ 8 GeV for L=2900 km
- $E_{\nu,MAX}$ □ 20 GeV for L=7400 km

Matter affects L/E scaling

$$\sin^2 2\theta_m(D) = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\pm\frac{D}{\Delta m^2} - \cos 2\theta\right)^2}$$

$$\lambda_m = L \times \sqrt{\sin^2 2\theta + \left(\pm\frac{D}{\Delta m^2} - \cos 2\theta\right)^2}$$

+ for neutrinos
– for antineutrinos

where

$$D(E_\nu) = 2\sqrt{2} G_F n_e E_\nu \approx 7.56 \times 10^{-5} \quad eV^2 \left(\frac{\rho}{gcm^{-3}}\right)\left(\frac{E}{GeV}\right)$$

For example, for neutrinos:

Resonance: $D \approx \Delta m^2 \cos 2\theta$ → $\sin^2 2\theta_m(D) \approx 1$

Suppression: $D > 2\Delta m^2 \cos 2\theta$ → $\sin^2 2\theta_m(D) < \sin^2 2\theta$

Mixing in matter smaller than in vacuum

Effect tends to become "visible" for L > 1000 km

Maximal length for L/E scaling

The magnitude of the CP effect (given by J) is known to be unaffected by matter

$J = \cos\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}/8$

Our "choice-point" for CP is at the fixed L/$E_{\nu,max}$ given by: $E_{\nu,\max} = \frac{2 \times 1.27 \times \Delta m^2 L}{\pi}$

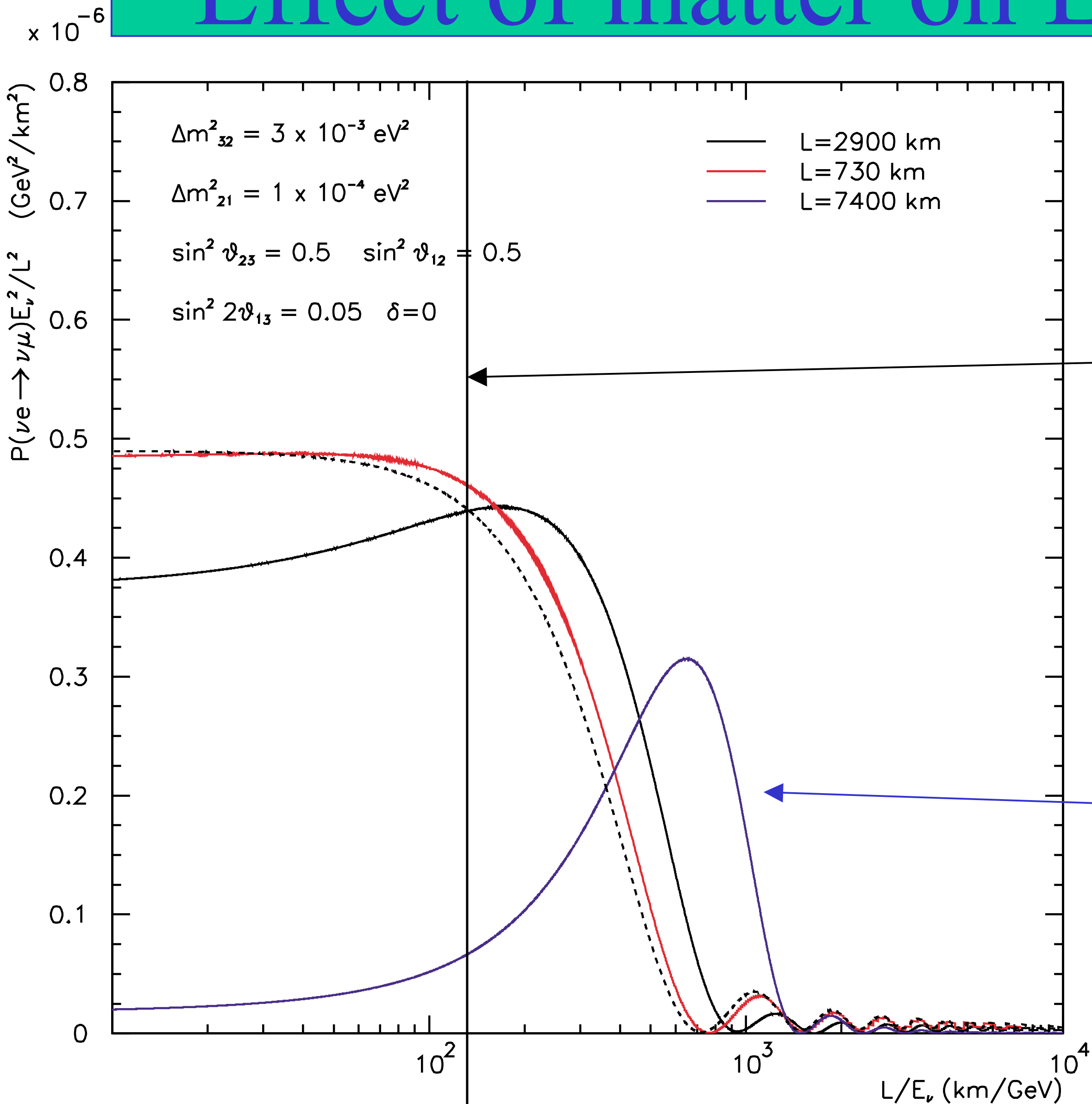
When the neutrino energy becomes close to the MSW resonance, the effective oscillation wavelength increases, hence the CP effect at a fixed distance L becomes less visible.

Hence, we gain until the MSW resonance region and then lose

$$2\sqrt{2} G_F n_e E_\nu < \Delta m^2 \cos 2\theta \Rightarrow 2\sqrt{2} G_F n_e \frac{2 \times 1.27 \Delta m^2 L}{\pi} < \Delta m^2 \cos 2\theta$$

$$L < \frac{\pi \cos 2\theta}{2 \times 1.27 \times 7.56 \times 10^{-5} \quad eV^2 \left(\frac{\rho}{gcm^{-3}} \right)} \approx \frac{1.5 \times 10^4 \, km}{\left(\frac{\rho}{gcm^{-3}} \right)} \approx 5000 km$$

Effect of matter on L/E scaling



MSW resonance position E_{MSW} □ 12 GeV

When

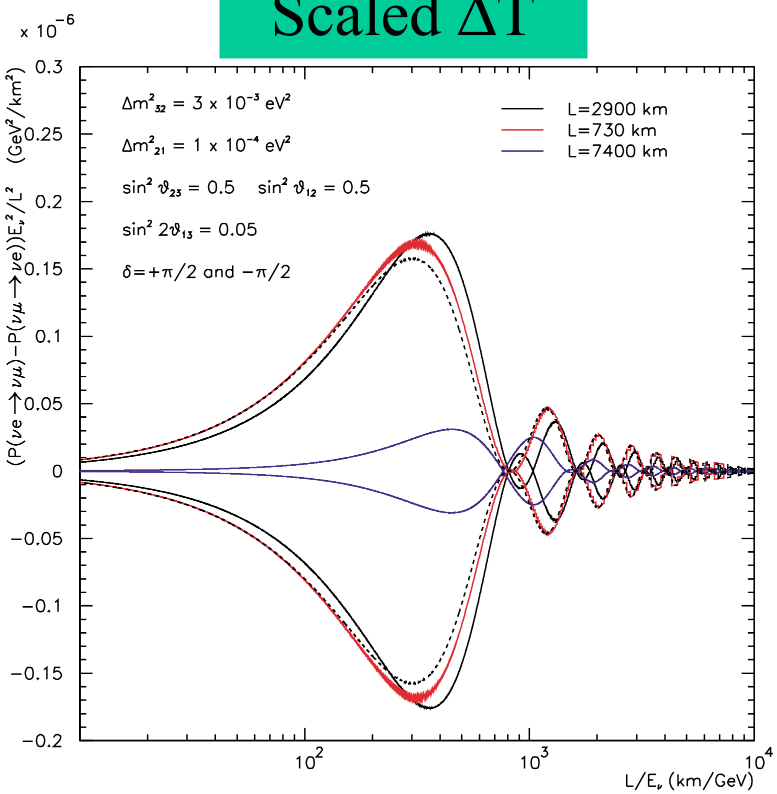
$E_{\nu,max} > E_{MSW}$,

the oscillation gets suppressed

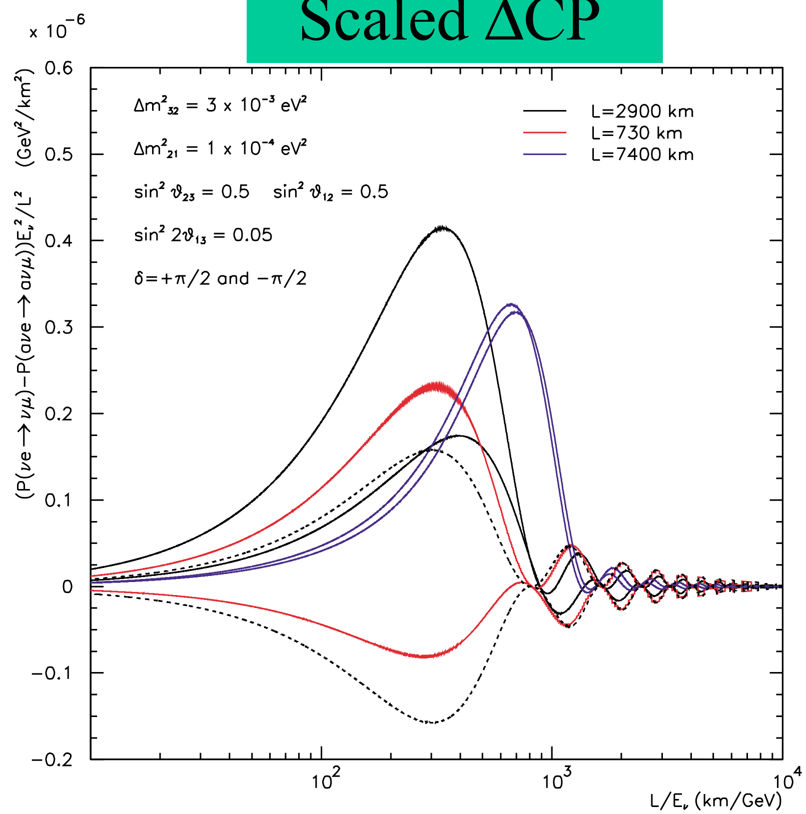
$D \approx 2\Delta m^2 \cos 2\theta$

CP- and T-violation in matter

Scaled ΔT



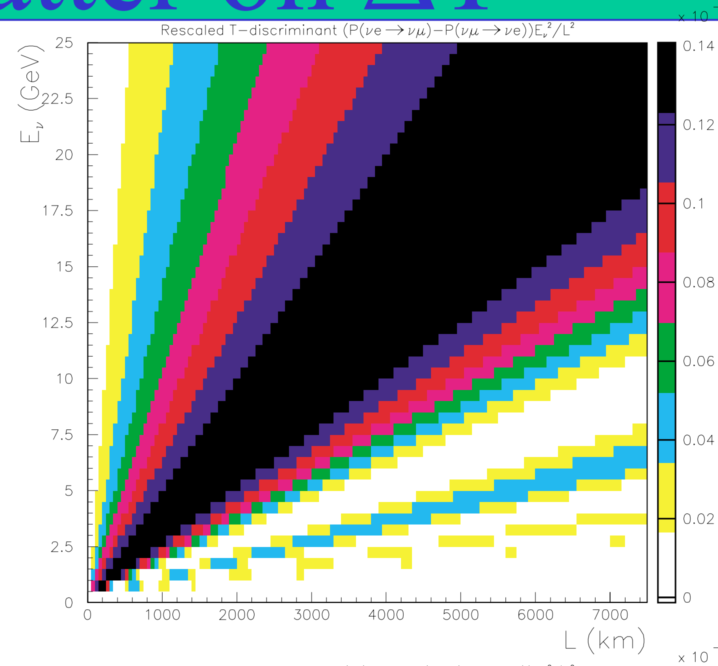
Scaled ΔCP



Experimental observables: for both ΔCP and ΔT, the difference between δ=π/2 and δ=-π/2 is suppressed at L=7400 km ($E_{\nu,MAX}$= 20 GeV > E_{MSW})

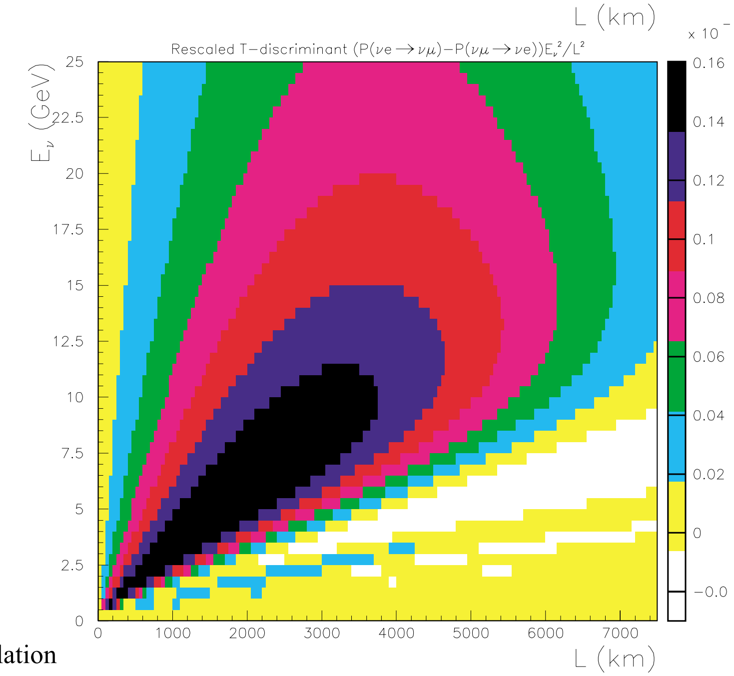
Effects of matter on ΔT

The cut-off of the scaled T-violating term in matter for L□4000 km destroys L/E scaling. It is useless to go above this distance for T-and CP-violation studies



vacuum

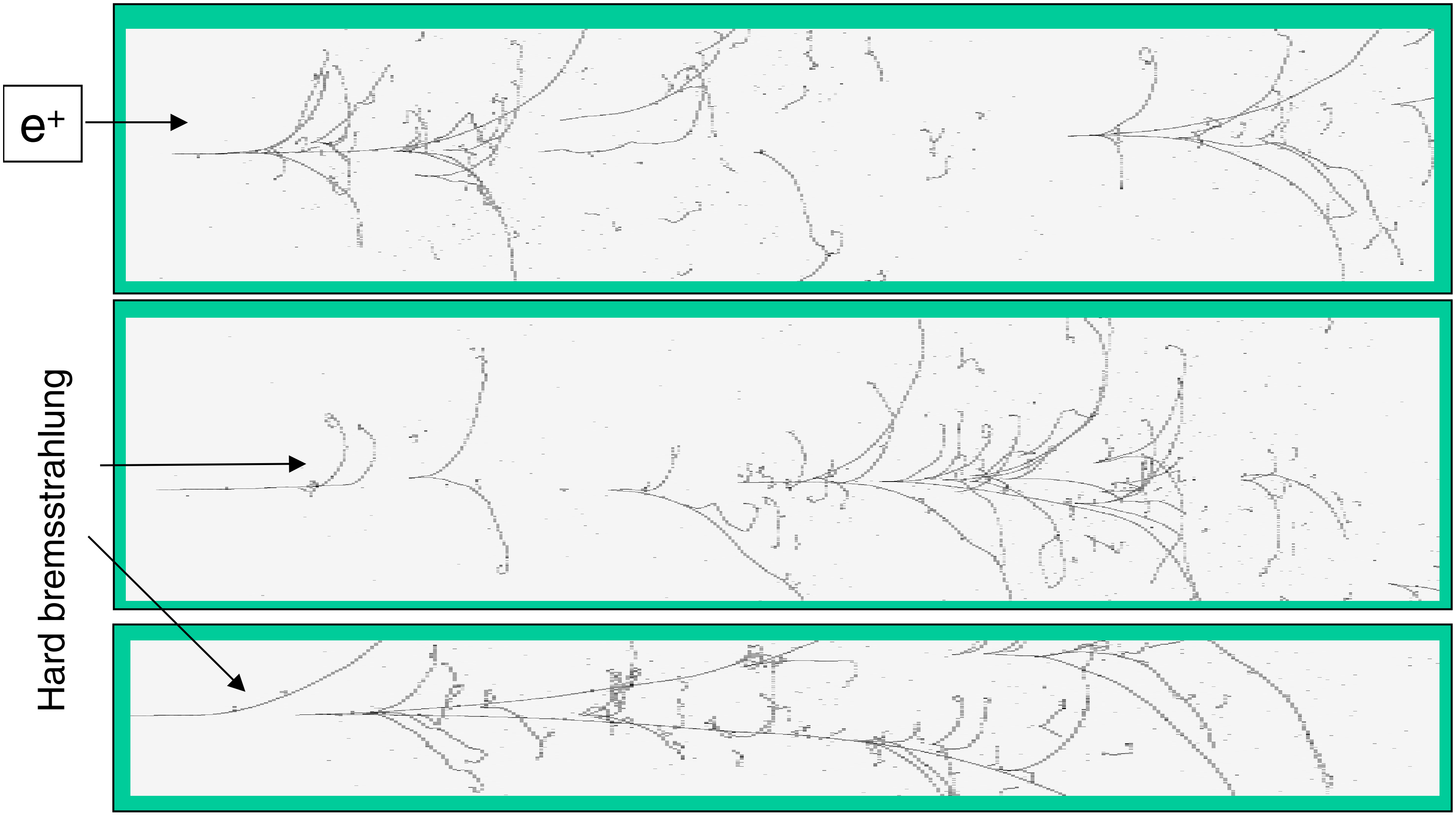
The above considerations have nothing to do with the necessity of subtracting fake-CP violation due to matter ν-$\bar{\nu}$ asymmetry



matter

Electron charge

In a granular detector (σ_x □ 100 μm) with a magnetic field of about 1T, bending of low-energy (E_e <□ 5 GeV) electrons can be observed before the start of the shower:

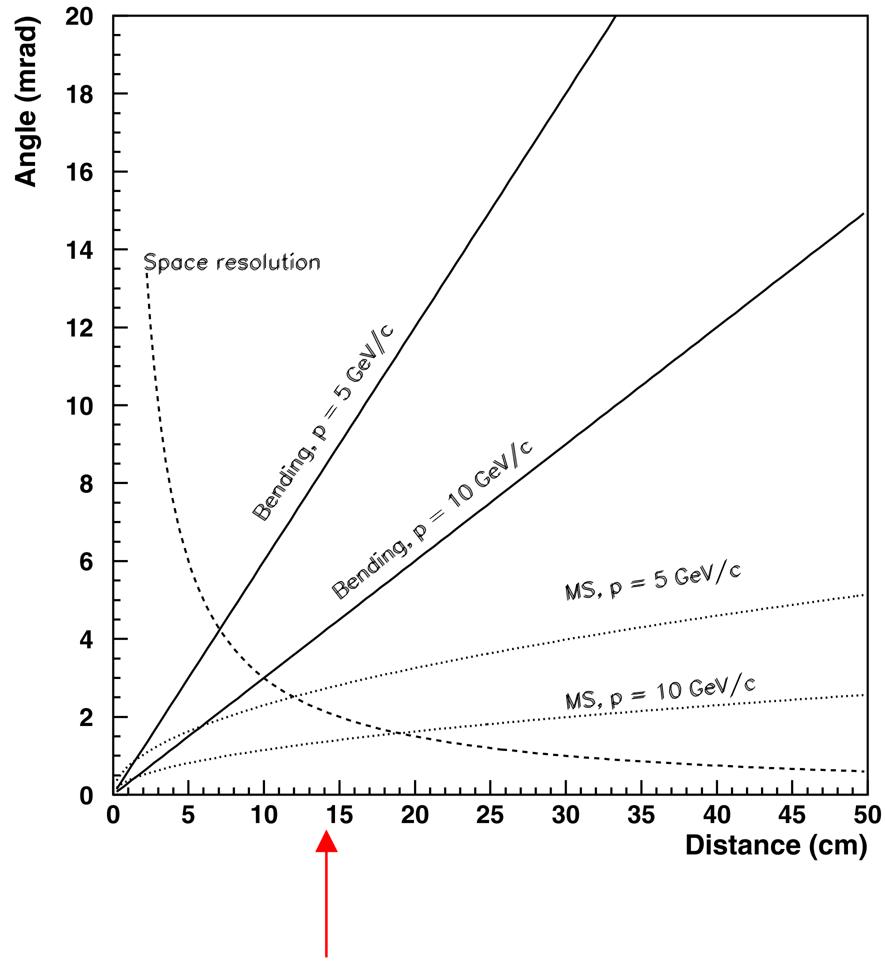


Energy-baseline considerations

For CP violation, L/E scaling breaks down for L□4000 km due to matter effects. The measurement is performed measuring the charge of muons, and detector efficiency is approximately constant over a wide energy range

For T-violation, the electron charge has to be measured. This is only practically conceivable for energies <□ 5 GeV

→low energies/short baselines needed!



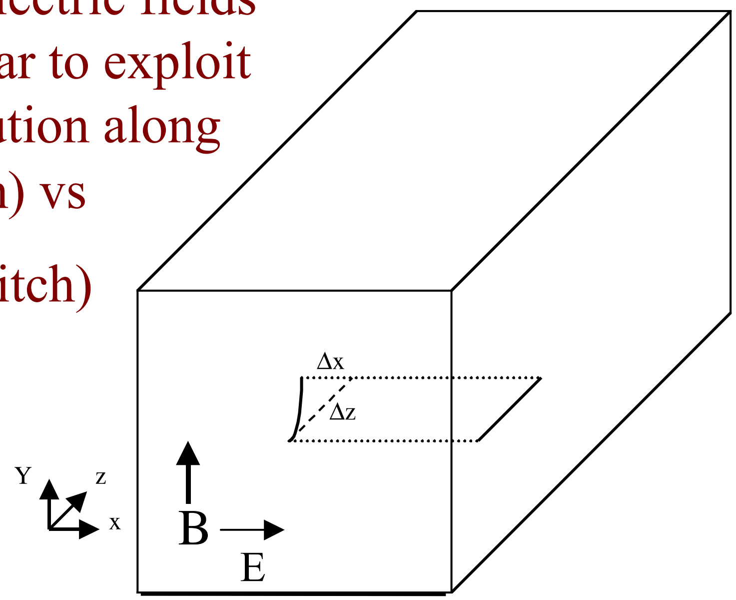
Radiation length of a light material (ex. LAr)

MC simulation for electron charge

MC simulations of electrons in a magnetic field have been performed, assuming the following magnet parameters:

Parameter	
Argon volume	$8 \times 8 \times 16 m^3$
Argon mass	1.4 kton
Magnetic field	1.0 T
Current	2000 A
Conductor length	150 km
Resistance	1 Ω
Dissipated power	4 MW
Iron mass	5 kton

Magnetic and electric fields are perpendicular to exploit the better resolution along drift (O(300 µm) vs O(3mm) wire pitch)



Purities obtained (for 10% efficiency) are encouraging, but clearly require high fields

B field (T)	Charge confusion (%)
0.2	35
0.5	15
1.0	3

1

For a practical implementation of a magnetized LAr TPC see talk from F.Sergiampietri

A practical example

In order to prove L/E scaling, and explore the physical reach in practical examples, we have studied in detail two cases:

- L= 732 km, E_μ = 7.5 GeV, 10^{21} μ decays for ΔCP and ΔT (also higher flux considered)
- L=2900 km, E_μ = 30 GeV, $2.5*10^{20}$ μ decays for ΔCP only

Event rates

10^{21} muon decays

10 kton detector

Assume BG rejection factor for electrons $O(10^{-3})$ for 20% efficiency

$\tau \rightarrow e$ background: another reason to require low energies!

	Process	$E_\mu = 7.5$ GeV, $L = 732$ km, 10^{21} μ^-	$E_\mu = 30$ GeV, $L = 2900$ km, 2.5×10^{20} μ^-
Non-oscillated rates	ν_μ CC	41690	36050
	ν_μ NC	10700	10300
	$\bar{\nu}_e$ CC	14520	13835
	$\bar{\nu}_e$ NC	4266	4975
Oscillated events ($\delta = \pi/2$)	$\bar{\nu}_e \rightsquigarrow \bar{\nu}_\mu$ CC	88	50
	$\nu_\mu \rightsquigarrow \nu_e$ CC	258	238
Oscillated events ($\delta = 0$)	$\bar{\nu}_e \rightsquigarrow \bar{\nu}_\mu$ CC	100	54
	$\nu_\mu \rightsquigarrow \nu_e$ CC	385	333
Oscillated events ($\delta = -\pi/2$)	$\bar{\nu}_e \rightsquigarrow \bar{\nu}_\mu$ CC	100	55
	$\nu_\mu \rightsquigarrow \nu_e$ CC	376	330

μ^- beam

	Process	$E_\mu = 7.5$ GeV, $L = 732$ km, 10^{21} μ^+	$E_\mu = 30$ GeV, $L = 2900$ km, 2.5×10^{20} μ^+
Non-oscillated rates	$\bar{\nu}_\mu$ CC	16570	15962
	$\bar{\nu}_\mu$ NC	5096	5600
	ν_e CC	37570	32100
	ν_e NC	9143	9175
Oscillated events ($\delta = \pi/2$)	$\nu_e \rightsquigarrow \nu_\mu$ CC	445	397
	$\bar{\nu}_\mu \rightsquigarrow \bar{\nu}_e$ CC	86	46
Oscillated events ($\delta = 0$)	$\nu_e \rightsquigarrow \nu_\mu$ CC	438	387
	$\bar{\nu}_\mu \rightsquigarrow \bar{\nu}_e$ CC	86	45
Oscillated events ($\delta = -\pi/2$)	$\nu_e \rightsquigarrow \nu_\mu$ CC	289	277
	$\bar{\nu}_\mu \rightsquigarrow \bar{\nu}_e$ CC	77	42

μ^+ beam

L/E scaling

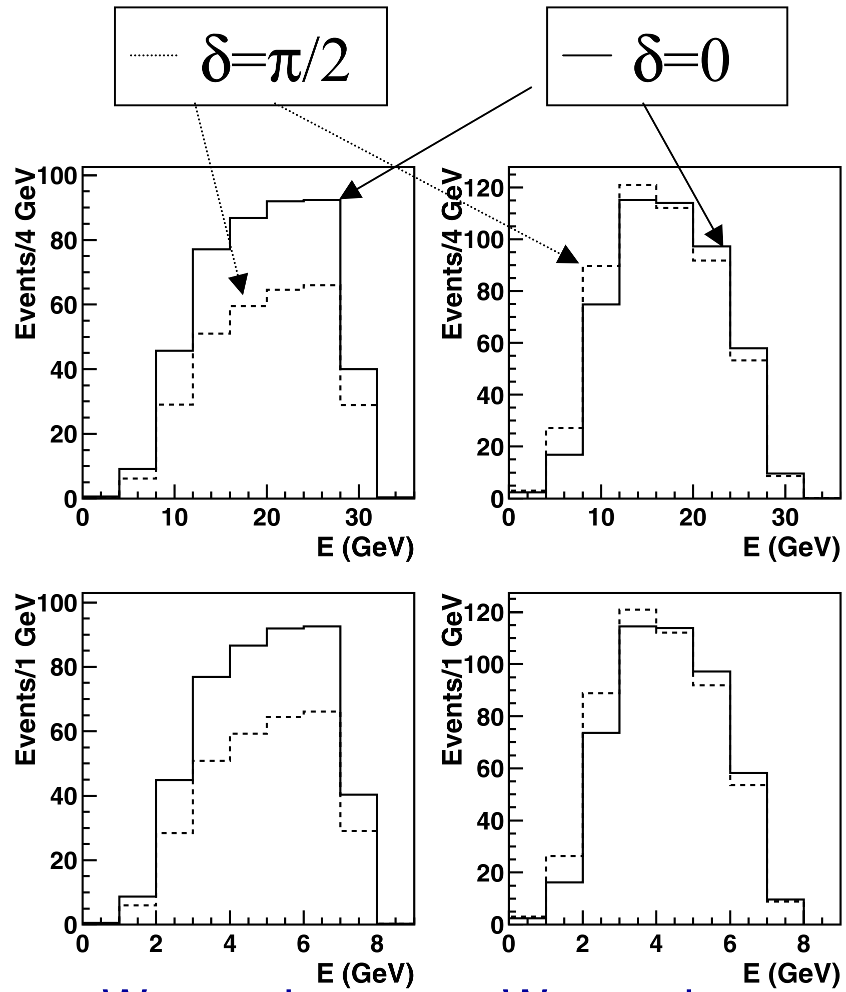
Also the number of oscillated events around the oscillation maximum depends on L/E

The integral below the maximum goes like E^3/L^2, so it is linear in L for a given L/E

However, for constant machine power,

$N_\mu * E_\mu$ = const,

so CP-violating effects only depend on L/ E_μ.



L=2900 km, E_μ=30 GeV

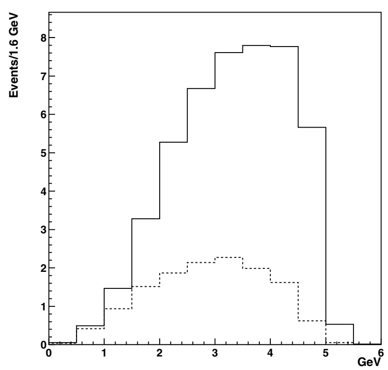
L=732 km, E_μ=7.5 GeV

Wrong-sign electrons

Wrong-sign muons

Direct measurement of oscillation

In addition to the MonteCarlo-based fit to the observed spectra, information about ΔCP and ΔT can be directly extracted from the oscillation probability:



Observed WSL events

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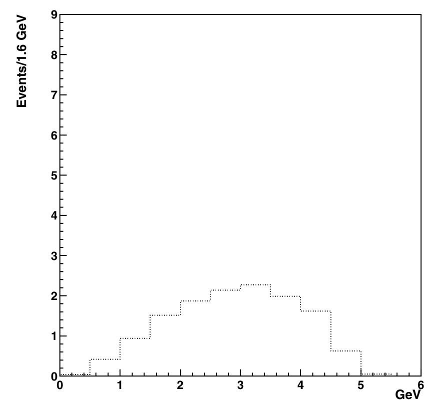

Background

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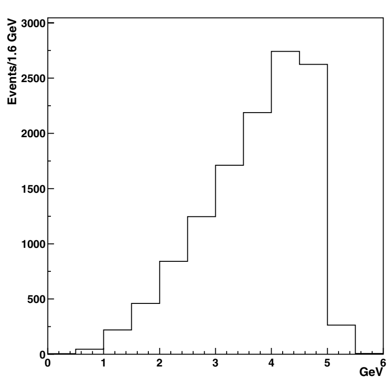

Non-oscillated

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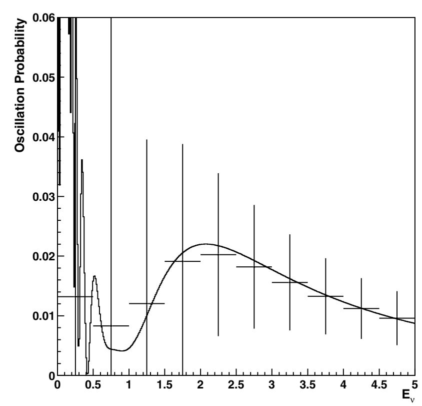
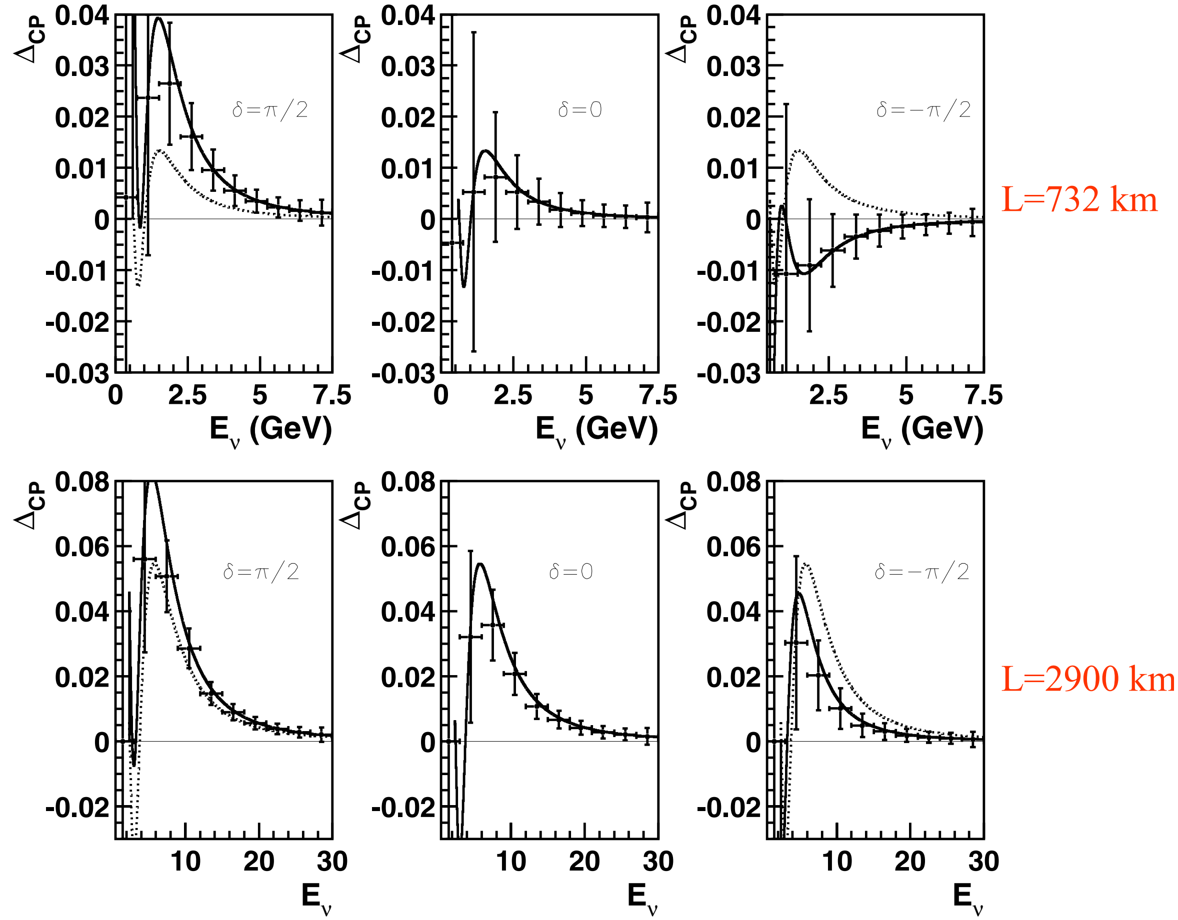


Oscillation probability

Measuring CP violation

The $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ oscillation probabilities obtained from wrong-sign muons.

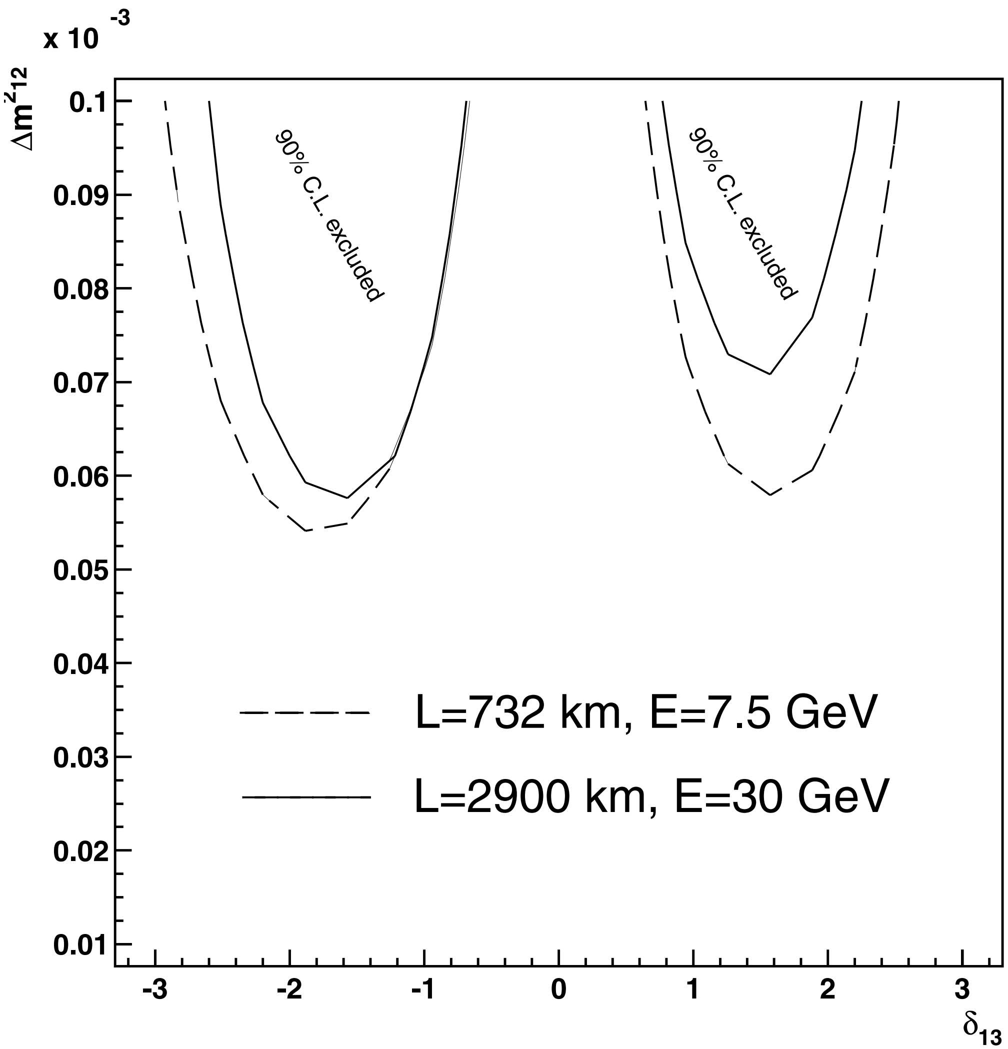


$\Delta CP = P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$,

Will be different from zero due to matter effects, even for $\delta=0$

At L=732 km, matter effects are smaller, and large negative values of δ can reverse the sign of ΔCP

L/E_μ scaling at work



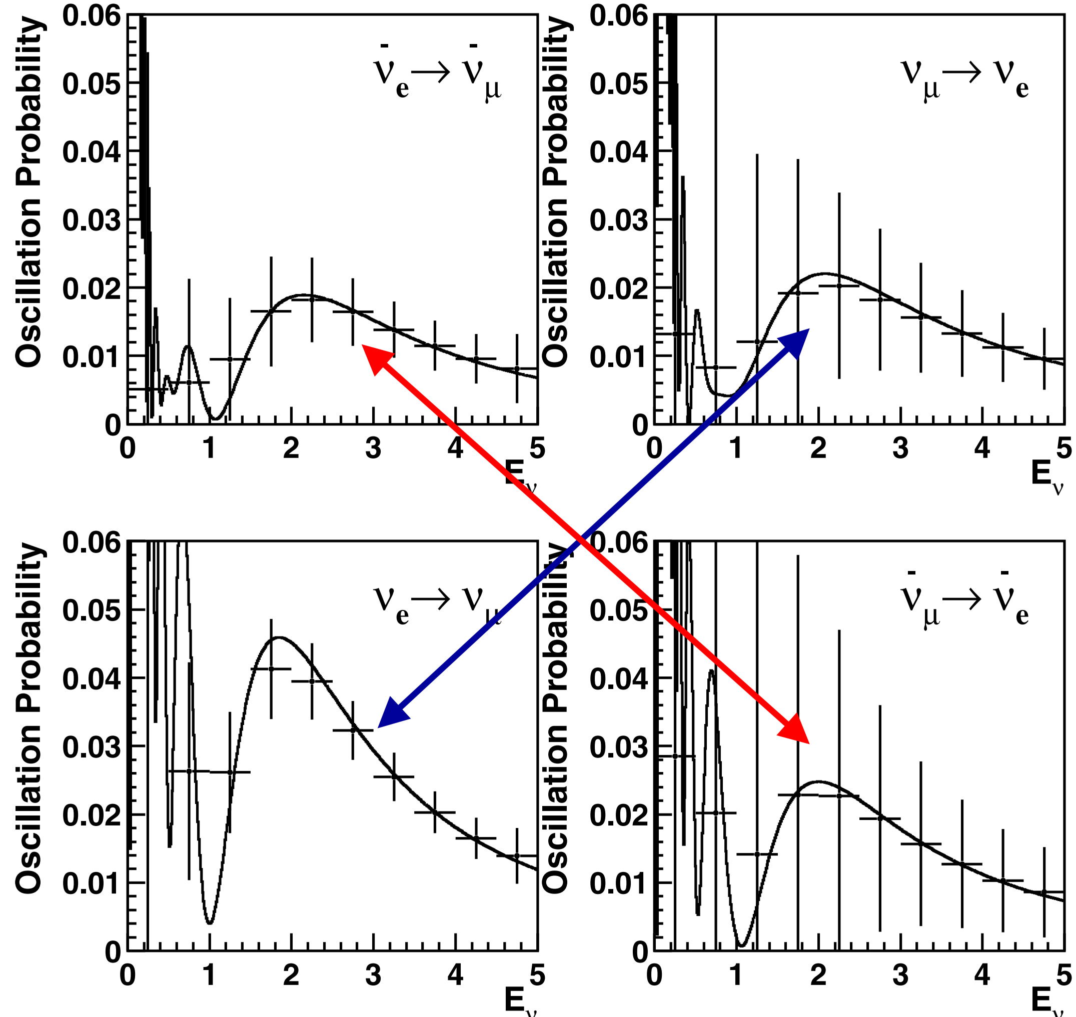
90% contours in the Δm^2_{12}-δ plane, obtained translating the probability differences into $\Delta\chi^2$

The sensitivity for the two cases is similar, proving the validity of the L/E_μ scaling at constant machine power. Actually, the shorter distance is even better due to the smaller influence of matter effects

Measured probabilities for T-violation

- $\Delta m^2_{23} = 3.5 \times 10^{-3}\ \mathrm{eV}^2$
- $\Delta m^2_{12} = 1. \times 10^{-4}\ \mathrm{eV}^2$
- $\sin^2 2\theta_{13} = 0.05$
- $\sin^2 2\theta_{23} = 1.$
- $\sin^2 2\theta_{12} = 1.$
- $\delta_{13} = \pi/2$
- 10^{21} μ decays
- 10 kton detector
- 20% e charge eff.

$E_\mu = 5$ GeV, L=732 km

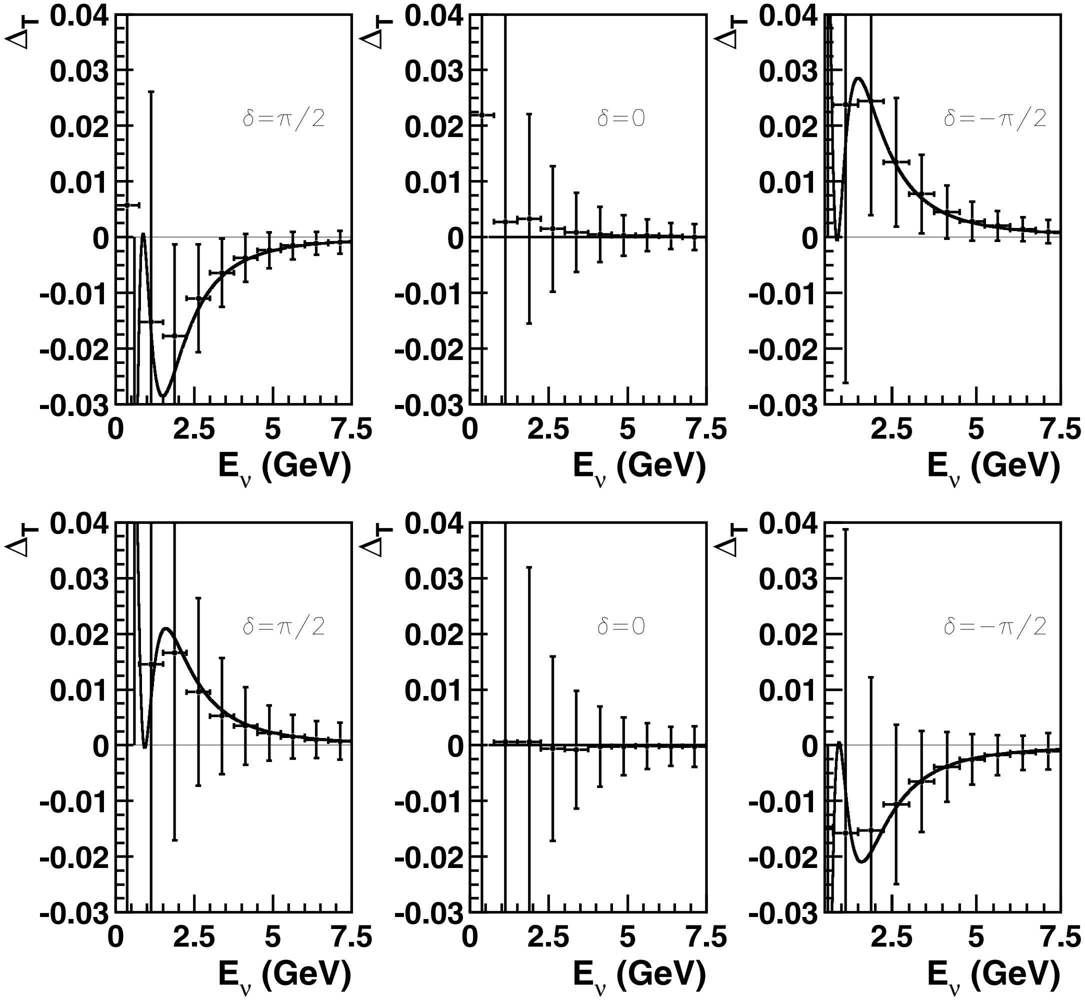


Direct comparison of oscillation probabilities for neutrinos and antineutrinos

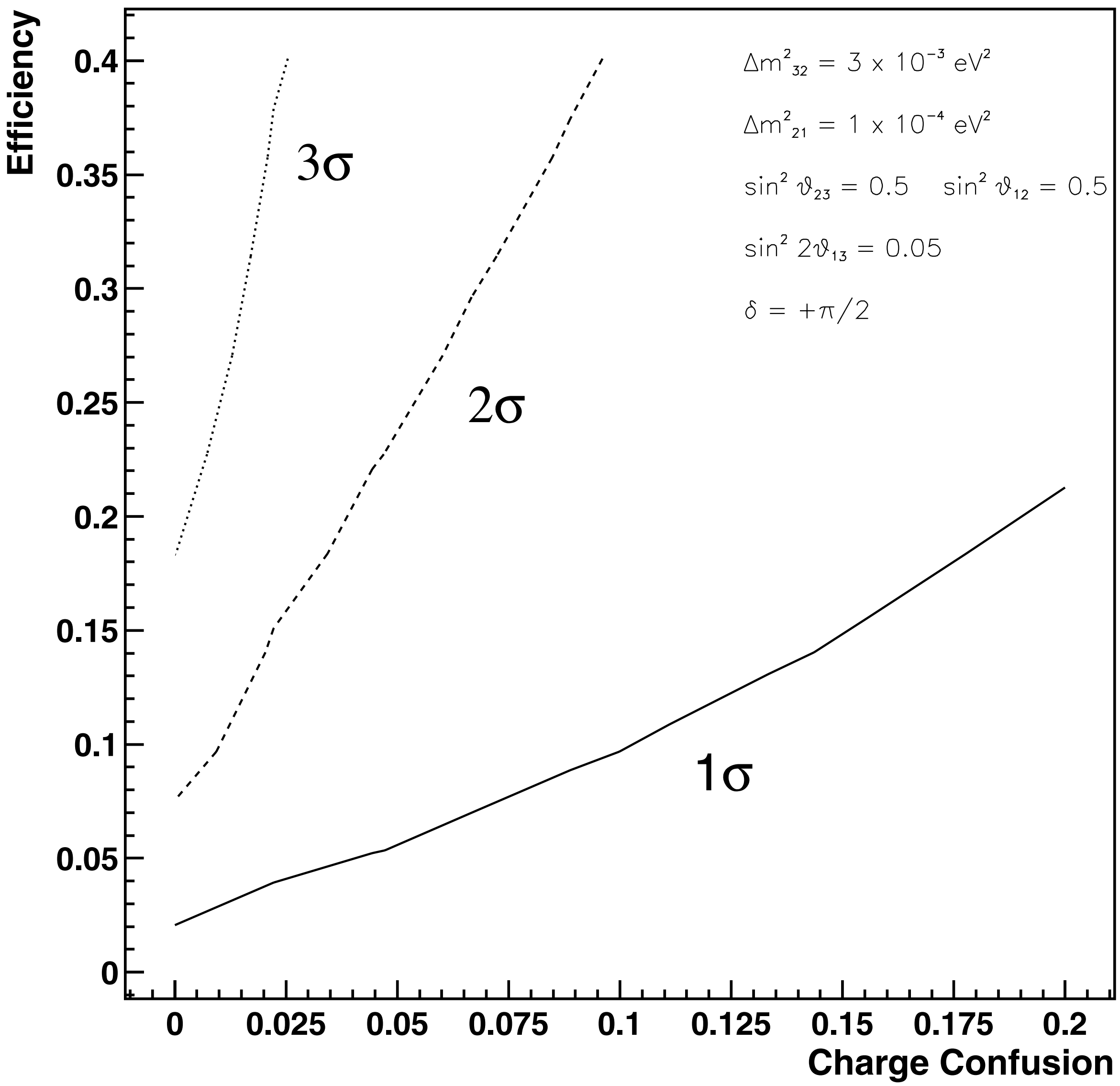
Measuring ΔT

The difference in probability for wrong-sign muons and wrong-sign electrons is a direct proof of T-violation. Matter effects are the same, and cancel out in the difference.

This measurement has a 3σ significance for δ=±π/2

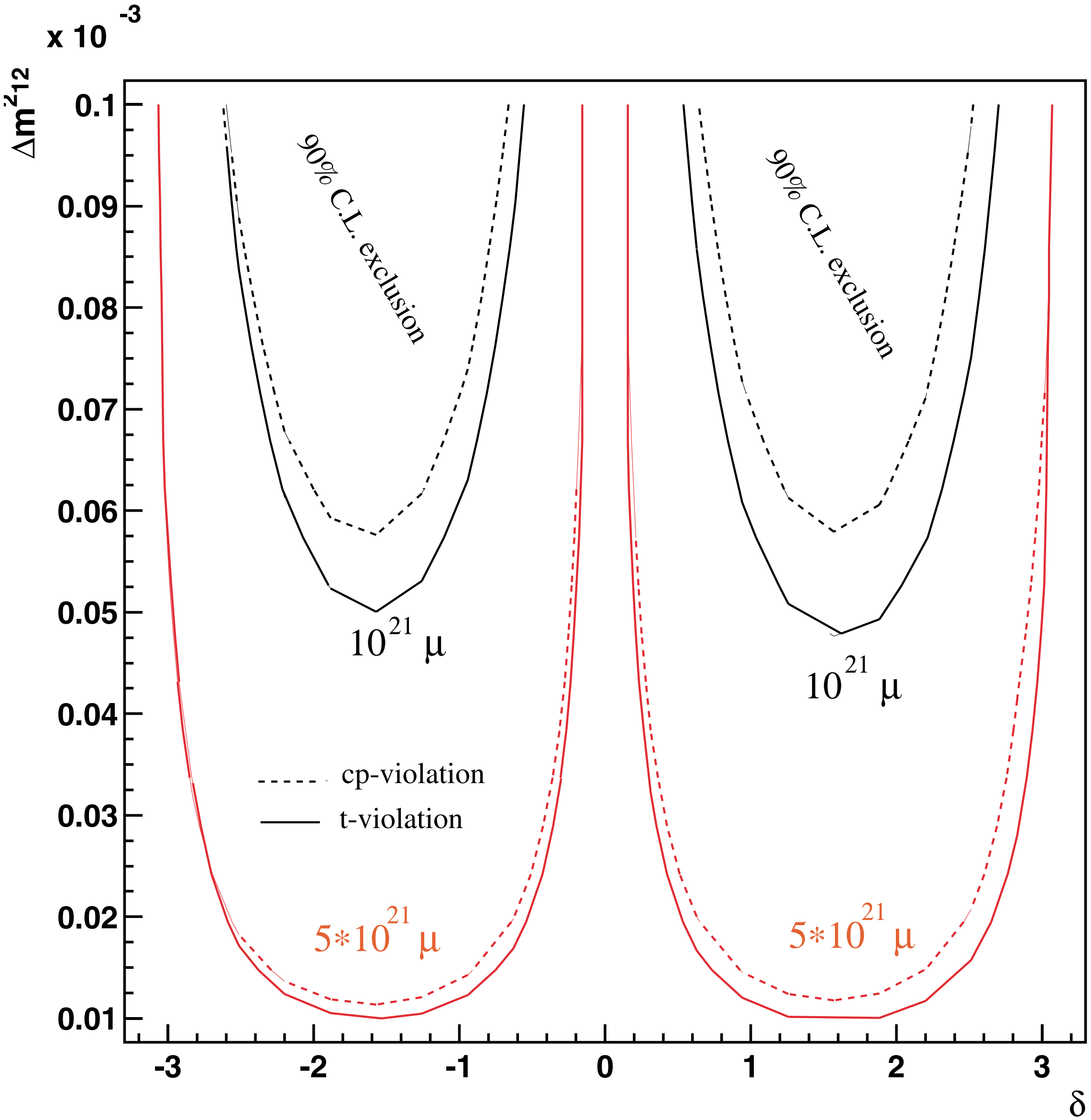


Efficiency-purity dependence



Due to the large background from the beam, a large purity is needed from the charge identification. However, charge confusion at 1% level does not spoil the measurement

ΔT exclusion



CP violation
and

T-violation

L=732 km

E_μ = 7.5 GeV

Conclusions

•In neutrino factory experiments, most of the sensitivity to CP-violation will come from events close to the first oscillation maximum

•Given the scaling laws for the number of events, for a given L/E_μ and a fixed flux, the sensitivity grows linearly with L until L<4000 km

•For fixed machine power, all energy/baseline combinations with same L/E_μ are equal. Baselines of □730 km, where existing facilities and experiments will be located at the time of the start of a neutrino factory can be used with an intense, low energy neutrino beam

•Matter effects are creating fake CP violation, but they are small for baselines <1000 km

•Matter effects can be fully eliminated searching for T-violation

•A detector with electron charge identification capabilities can provide a clean and model-independent evidence for a complex phase in the leptonic mixing matrix