CP- and T-violation studies in a medium- energy Neutrino Factory

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Introduction

raditionally, proposed CP-violation studies in a Neutrino Factory consist in exploiting the differences in the Wrong-Sign Muons (WSM) spectrum due to the effect of a nonzero δ phase.

Even for an optimistic choice of the parameters, this difference is tiny, and requires accurate detector description, since data are compared to MC only.

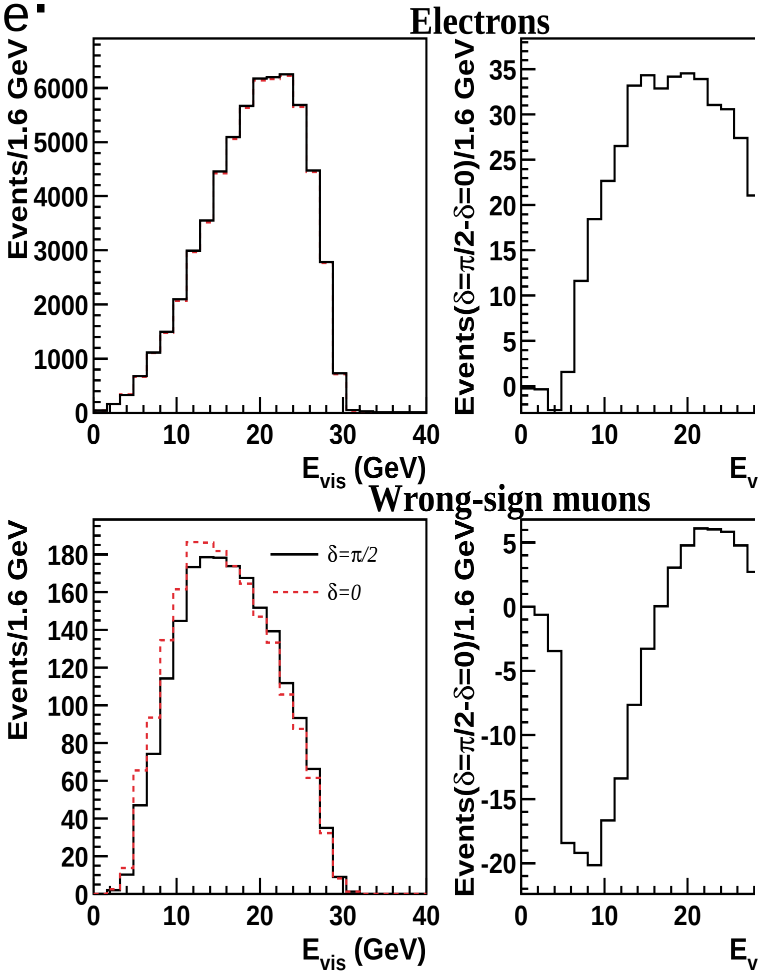
CP-violation

CP-violation affects electrons as well, but it drowns in a large background from beam ν_e.

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

$\hookrightarrow e^+$

$\hookrightarrow \nu_\mu 4\ \nu_e \rightarrow e^-$



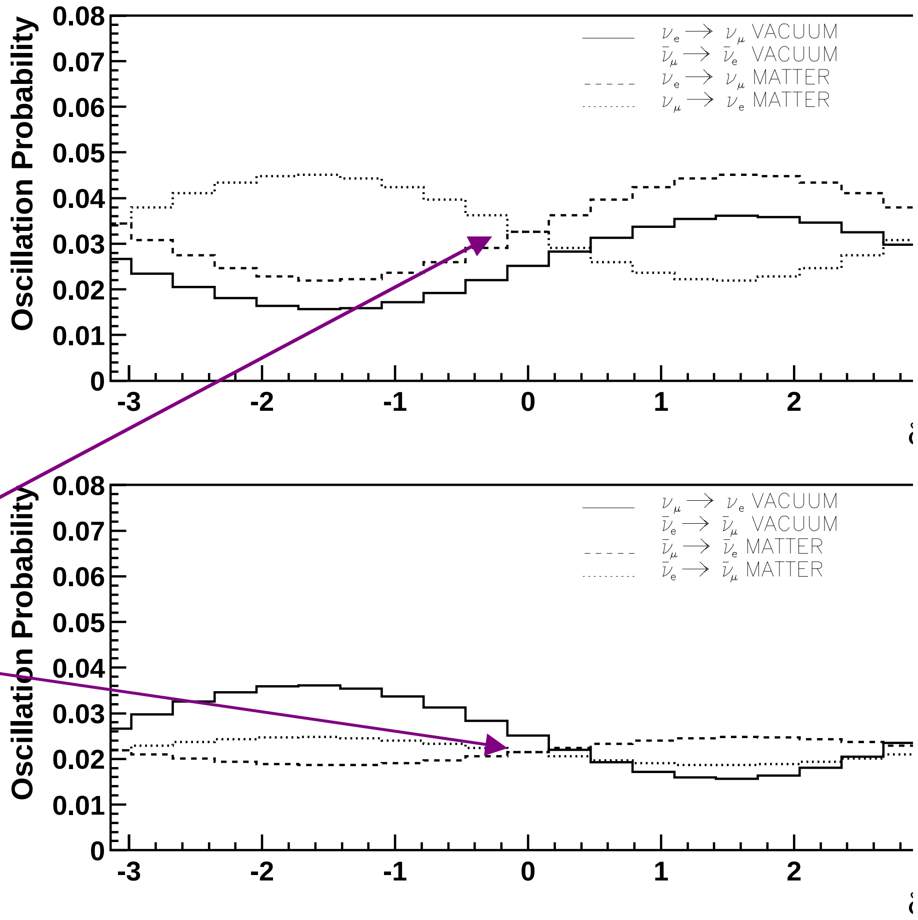
The electron component from beam prevents a direct comparison of $\nu_\mu 4\ \nu_e$ and $\nu_e 4\ \nu_\mu$ oscillations, i.e. a direct measurement of T-violation.

T-violation

For CPT theorem, magnitude of T- and CP-violation must be the same.

Matter propagation affects neutrinos and antineutrinos in a different way, creating a fake CP violation, dependent on earth density and oscillation parameters.

T-violation deals with differences between neutrinos only, so matter effects only give a scale factor.



Fake ~~CP~~, but no fake ~~T~~ for δ=0!

How to measure T violation

The comparison of $\nu_\mu 4\ \nu_e$ and $\nu_e\ 4\ \nu_\mu$ oscillation probabilities offers a direct way to highlight a complex component in the mixing matrix, independent of matter and other oscillation parameters.

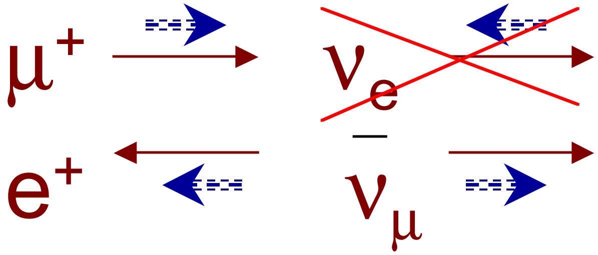
This measurement is not directly accessible at a Neutrino Factory due to large ν_e background in the beam. Two methods have been proposed to solve this problem:

Beam polarization

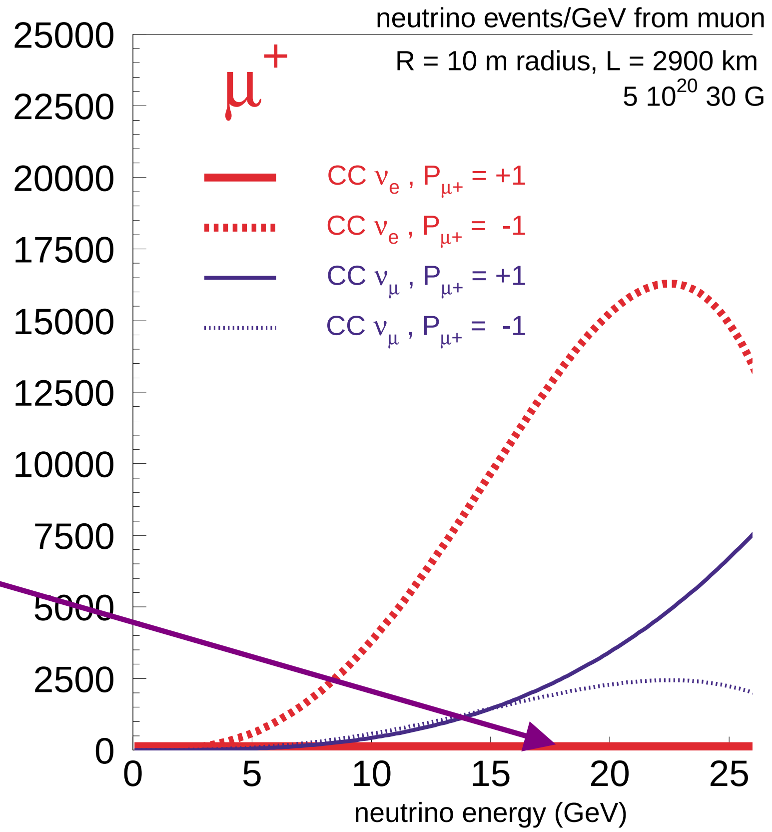
Electron charge

Polarization

onservation of angular momentum prevents ν_e from decaying in the forward direction for a fully-polarized muon beam



Electron component in forward detector disappears for $P_{\mu+}=+1$!



Polarization at work (doesn’t work)

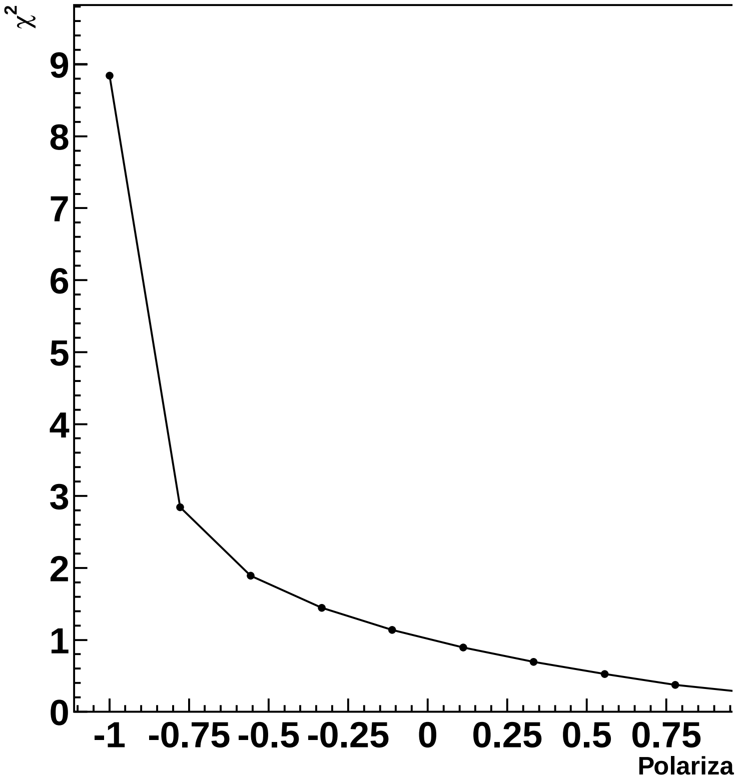
he relevance of polarization for CP-violation studies was already studied for Monterey.

inal outcome: to beat beam electrons, unrealistically large values of polarization are required.

Electron contribution to χ^2 for the CP fit.

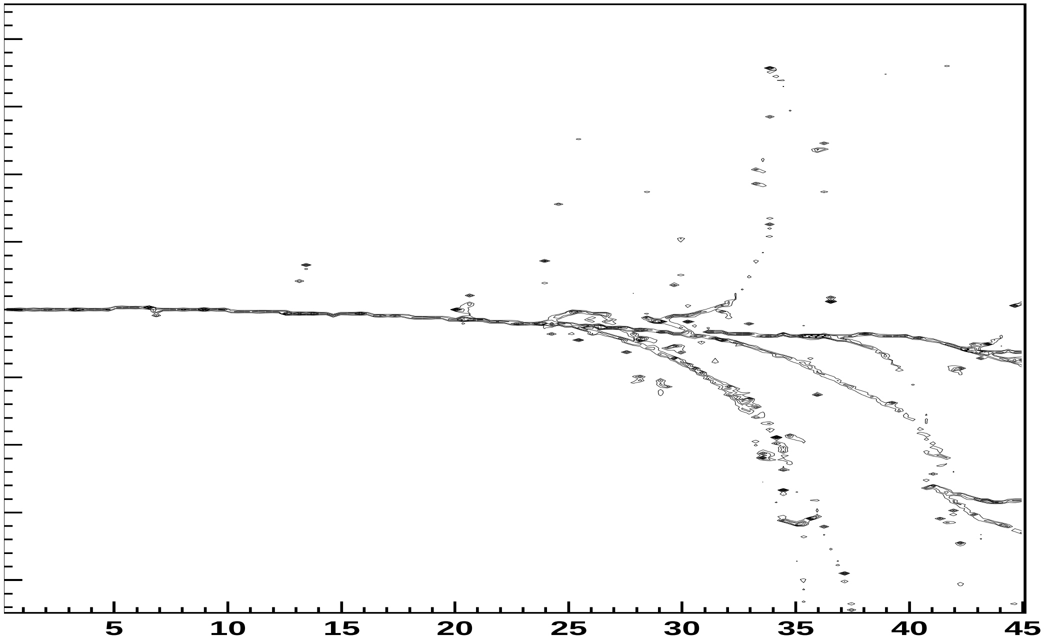
Only at high negative polarization electrons are competitive with wrong-sign muons ($\Delta\chi^2 = 5$).

Figures from: A.Blondel, A.Bueno, M.Campanelli, A.Rubbia, Monterey proceedings.

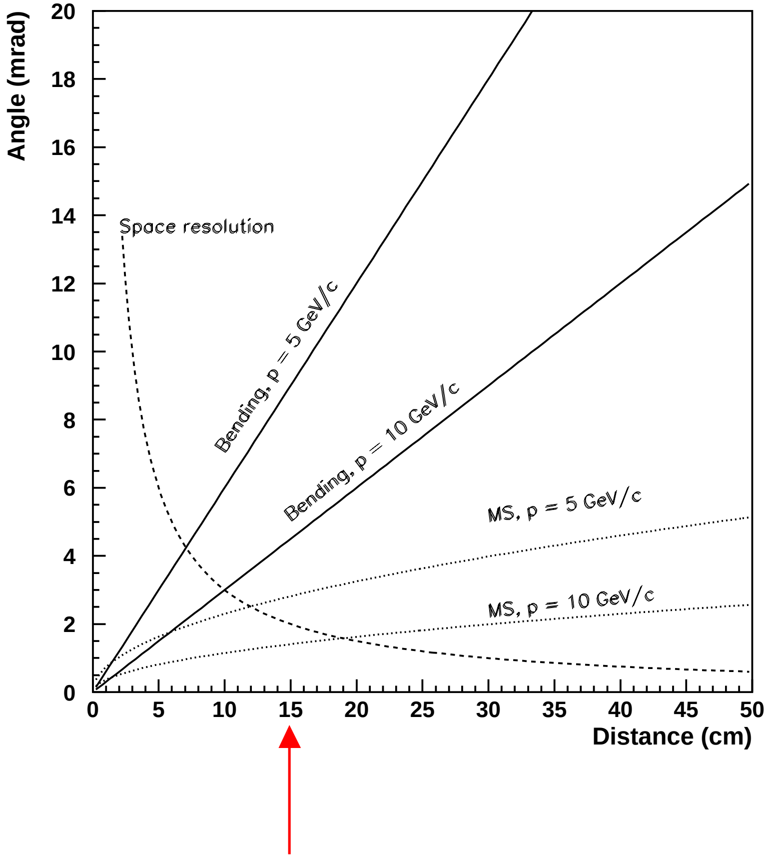


Electron charge

aving a detector with electron charge identification is not unfeasible. With 1T field, electrons can be sufficiently bent before they start showering;



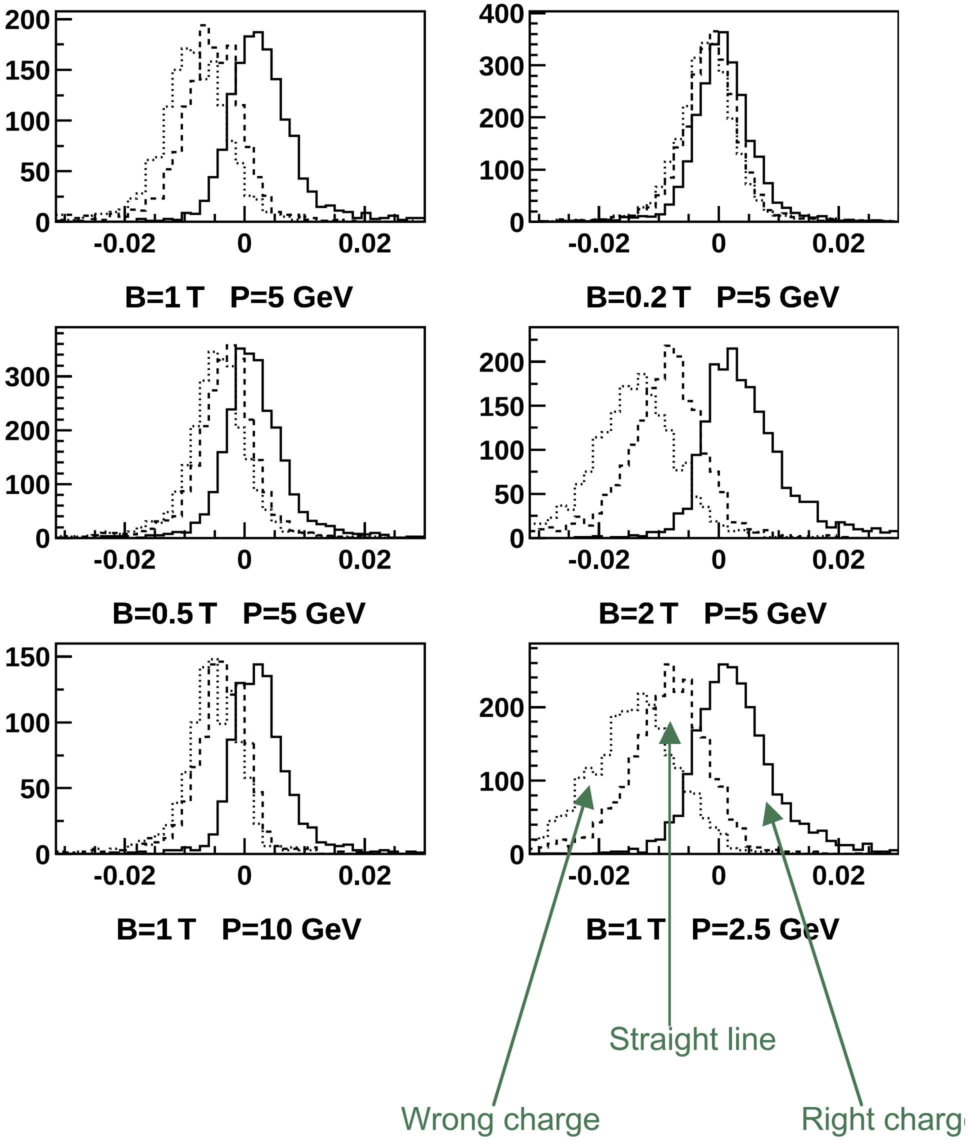
Fully simulated 2.5 GeV electron in LAr with 1T external field



Radiation length of a light material (ex. LAr)

Initial electron direction

A further source of uncertainty is the initial electron direction, not known a priori in CC interactions. Since energy is known, a fit with an arc with proper radius gives back angle with 5 mrad accuracy



B=1 T P=5 GeV

B=0.2 T P=5 GeV

B=0.5 T P=5 GeV

B=2 T P=5 GeV

B=1 T P=10 GeV

B=1 T P=2.5 GeV

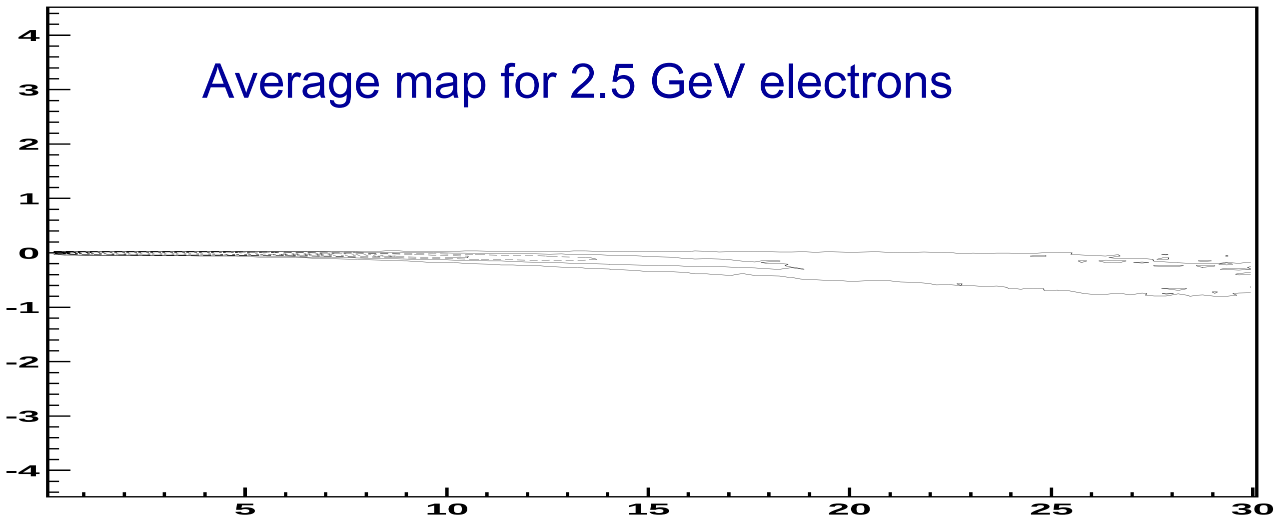
Straight line

Wrong charge

Right charg

Fit for electron charge

Finally, charge is determined using a likelihood fit, comparing the hits to an average map and its mirror image. Larger weight is given to hits before the shower development.



Work still in progress; however, background contamination O(10^{-3}) seem feasible for efficiencies O(10-20%) for E_e< 5 GeV.

Choice of energy/baseline

The need of low-energy electrons points towards lower-energy beams and shorter distances.

Let us re-consider for the whole energy/baseline optimization, in particular for CP-violation issues.

Neutrino oscillations and CP violation

Oscillation probability is given by a CP-even and a CP-odd term

$$P(\nu_\alpha \rightarrow \nu_\beta) = P_{\text{CP-even}}(\alpha,\beta;\, E,L) + P_{\text{CP-odd}}(\alpha,\beta;\, E,L)$$

$$P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = P_{\text{CP-even}}(\alpha,\beta;\, E,L) - P_{\text{CP-odd}}(\alpha,\beta;\, E,L)$$

CP-odd term (in vacuum)

$$P_{CP\text{-}odd}(\mu,e) = (P(\nu_e\rightarrow\nu_\mu)-P(\overline{\nu}_e\rightarrow\overline{\nu}_\mu))/2 =$$

$$(P(\nu_e\rightarrow\nu_\mu)-P(\nu_\mu\rightarrow\nu_e))/2 =$$

Basically1

Complex term in matrix

Need LA MSW

Oscillation goes like $\sin^2\theta_{13}$

$$2\cos^2\theta_{13}\,\sin\delta_{13}\,\sin2\theta_{12}\,\sin\theta_{13}\,\sin2\theta_{23}$$

$$\mathrm{in}(\Delta M^2_{12}\,L/4E)\,\sin(\Delta M^2_{13}\,L/4E)\,\sin(\Delta M^2_{23}\,L/4E)$$

Only depends on L/E !

Maximum of CP-odd effect

osition of first (and broader) maximum of CP-odd term is proportional to baseline

$E_{\text{CP-odd MAX}} = \alpha L$

α ¯ $1.27 \times 2 \times \Delta M^2_{23}/\pi$

¯ 2.8×10^{-3} for $\Delta M^2_{23} = 3.5\ 10^{-3}$ →

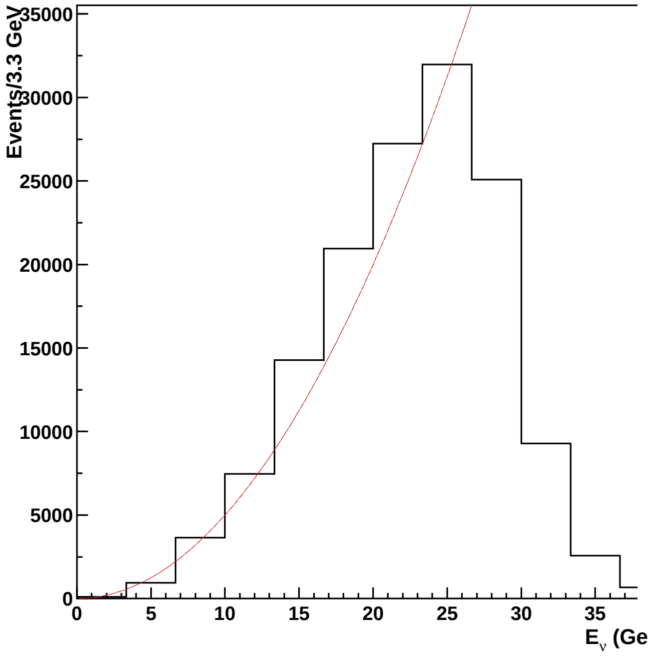
¥$E_{\text{CP-odd MAX}}$ ¯ 2 GeV for L=732 km

¥$E_{\text{CP-odd MAX}}$ ¯ 8 GeV for L=2900 km

Neutrino flux at Neutrino Factory

otal number of events at NF grows like E^3.

ι CC spectrum can be approximated by



$$dN/dE^{-}\ \beta E^2/L^2$$

Number of events at $E_{\text{CP-oddMAX}}$:

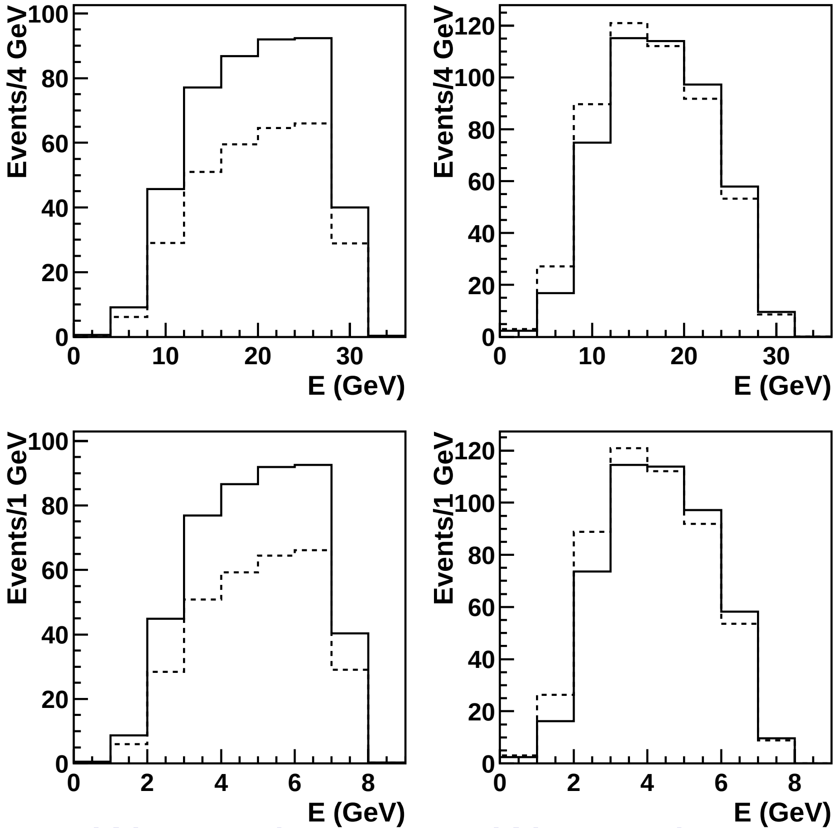
$$dN/dE_{\text{CP-odd MAX}}{}^{-}\ \ \beta E^2/L^2 = \beta\,(\alpha\,L)^2 = \beta\alpha^2$$

The number of events around the maximum of the CP-odd term is independent of L

L/E dependence

Not only the CP-odd probability, but also the number of oscillated events around the maximum only depends on L/E and not on the specific baseline.

For a given L/E_μ, the difference produced by CP violation is linear in L; however, for constant machine power, $N_\mu \propto 1/E_\mu$, 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

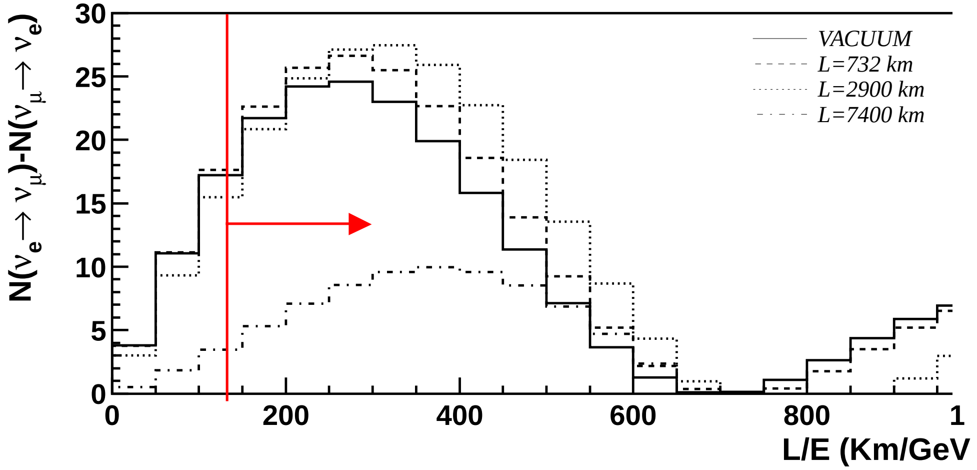
Wrong-sign electrons

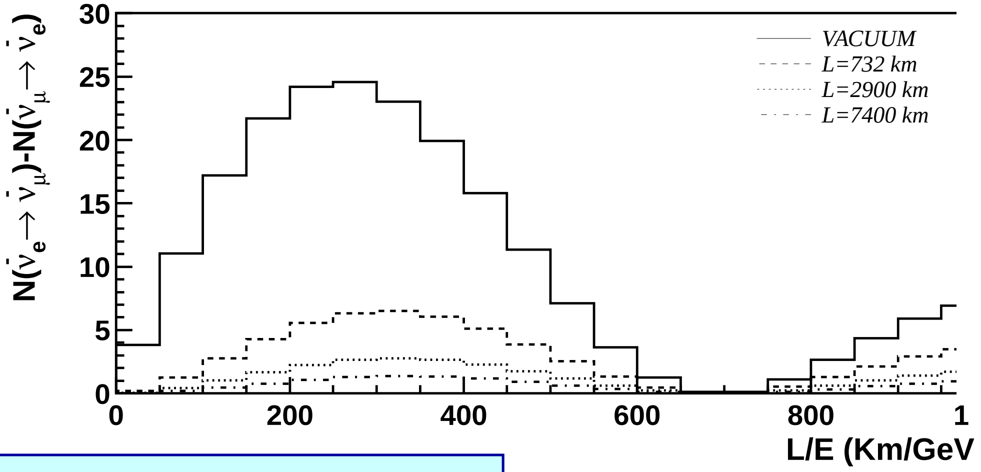
Wrong-sign muons

L/E dependence in matter

Matter effects do not change this picture in any significant way, unless L gets too big (L>5000 km).

For a given machine power, CP-violating effects will be ¯ the same, provided that L(km)/E $_\mu$(GeV) <¯ 200





We choose to work at L=732, E$_\mu$=5 GeV
(L/E¯ 140)

Event rates

10^{21} muon decays

10 kton detector

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

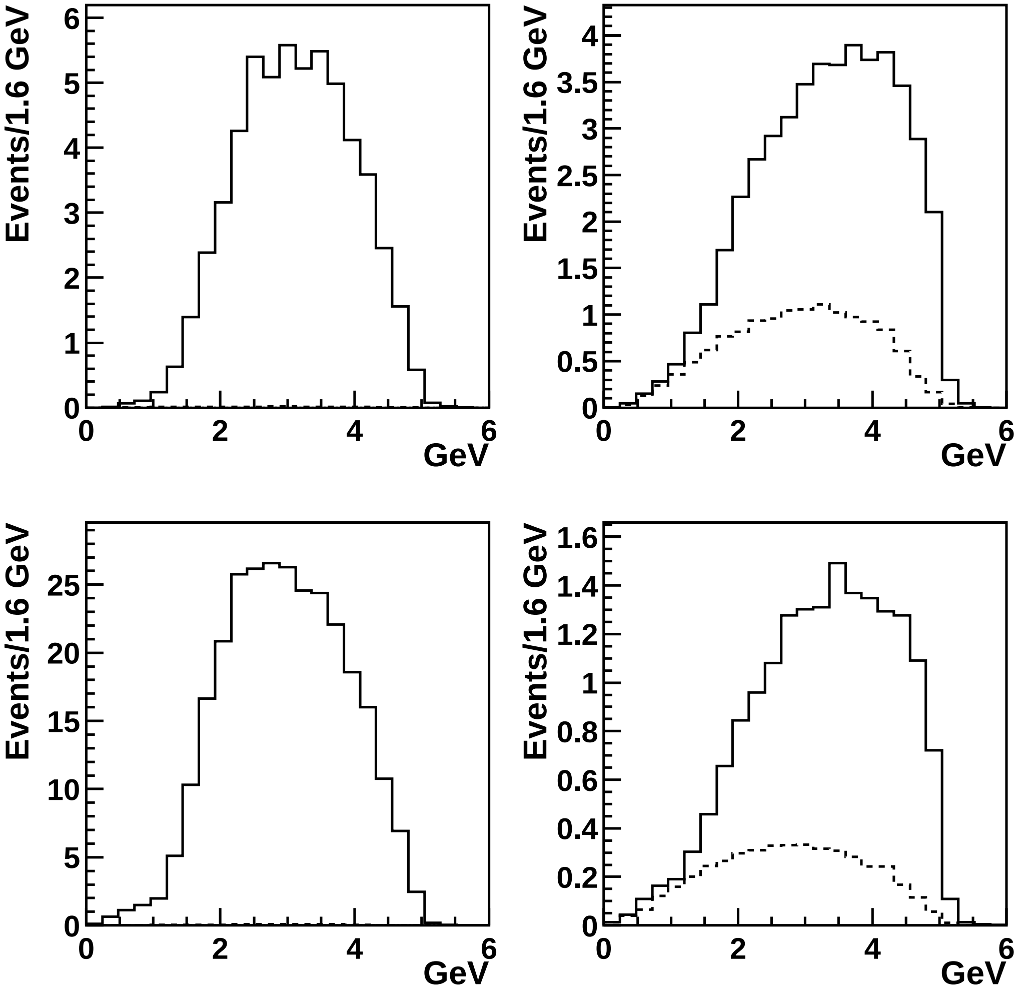
CP-violation effect

	Process	L=732 km μ^- decays	L=732 km μ^+ decays	L=2900 km μ^- decays	L=2900 k μ^+ decay
Nonoscillated rates	ν_μ CC	12354	4911	144200	63850
	ν_μ NC	3170	1510	41200	22400
	ν_e CC	4302	11133	55340	128400
	ν_e NC	1264	2709	19900	36700
Oscillated events ($\delta = \pi/2$)	ν_μ CC	56	289	269	2076
	ν_e CC	166	65	1312	249
	$\nu_\tau \to \mu$ CC	0.2	0.9	16	87
	$\bar{\nu}_\tau \to e$ CC	67	22	3333	1454
Oscillated events ($\delta = 0$)	ν_μ CC	65	249	286	1978
	ν_e CC	245	64	1732	248
	$\nu_\tau \to \mu$ CC	0.2	0.9	16	87
	$\bar{\nu}_\tau \to e$ CC	67	22	3333	1454
Oscillated events ($\delta = -\pi/2$)	ν_μ CC	68	170	291	1516
	ν_e CC	268	56	1747	233
	$\nu_\tau \to \mu$ CC	0.2	0.9	16	87
	$\bar{\nu}_\tau \to e$ CC	67	22	3333	1454

Wrong-sign lepton spectra

μ^- decays

μ^+ decays



WS ν_μ CC   WS ν_e CC

Main BG for WSE:

$\mu^-\to\nu_\mu 4\ \nu_\tau\to\tau^-\to e^-$

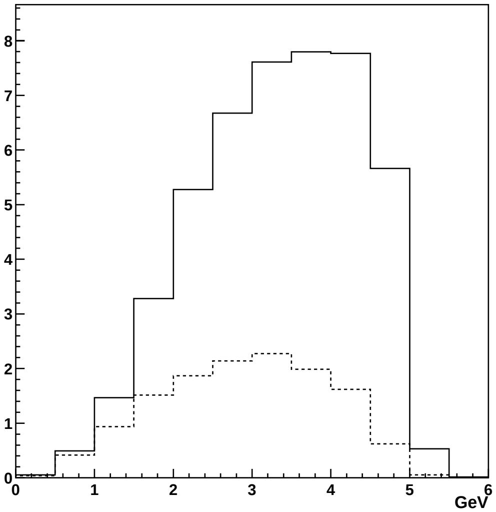
Wrong-sign electrons from τ decays not suppressed as in the WSM case:

$\mu^-\to\nu_e 4\ \nu_\tau\to\tau^+\to\mu^+$

$\propto\sin^2 2\theta_{13}$

One more reason to go to lower energies where τ production is suppressed

T-violation: the method



bserved WSL events

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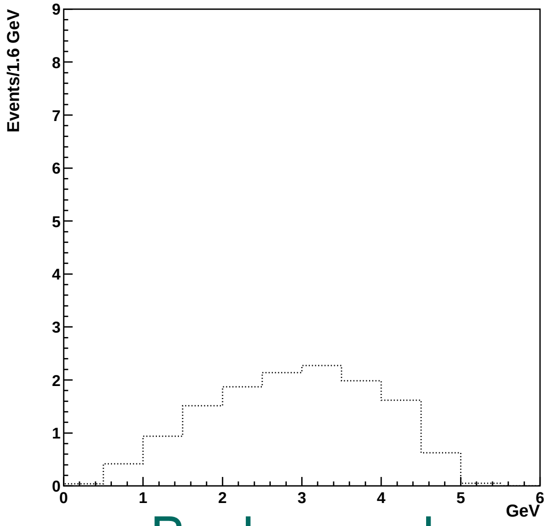

Background

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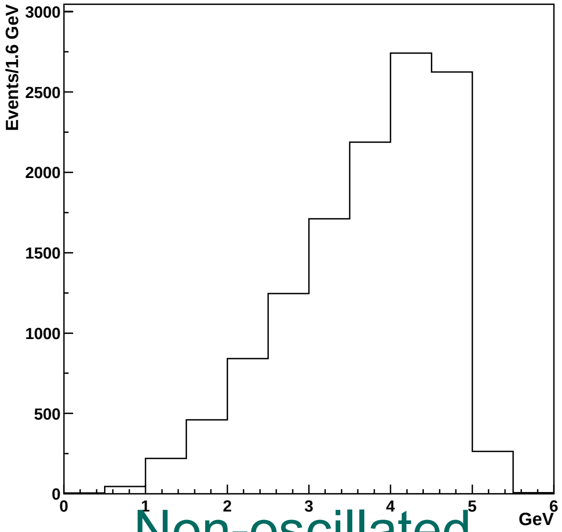
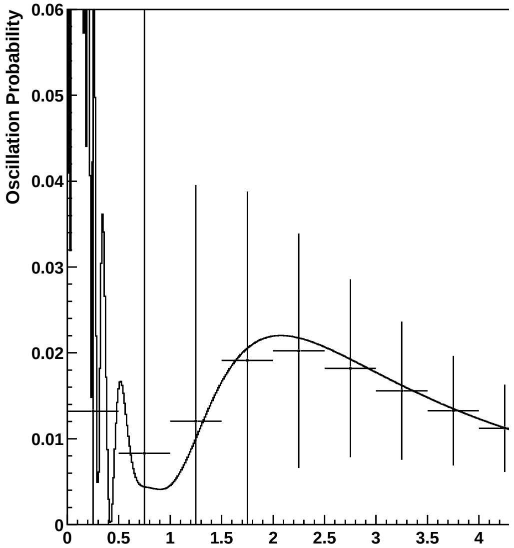


Non-oscillated

=



Oscillation probability

Measured oscillation probabilities

$\Delta m^2_{23}=3.5\subseteq 10^{-3}$ eV^2

$\Delta m^2_{12}=1.\subseteq 10^{-4}$ eV^2

$\sin^2 2\theta_{13}=0.05$

$\sin^2 2\theta_{23}=1.$

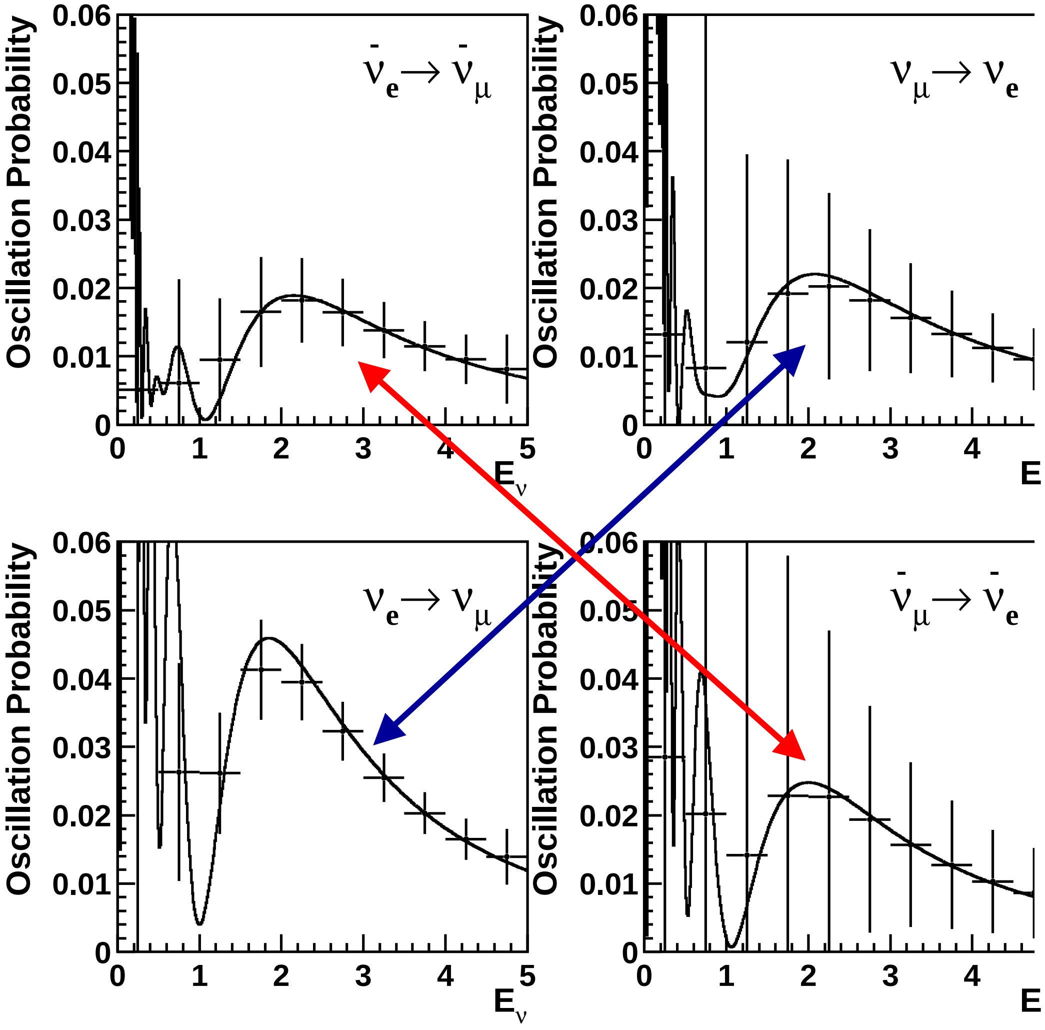
$\sin^2 2\theta_{12}=1.$

$\delta_{13}=\pi/2$

10^{21} μ decays

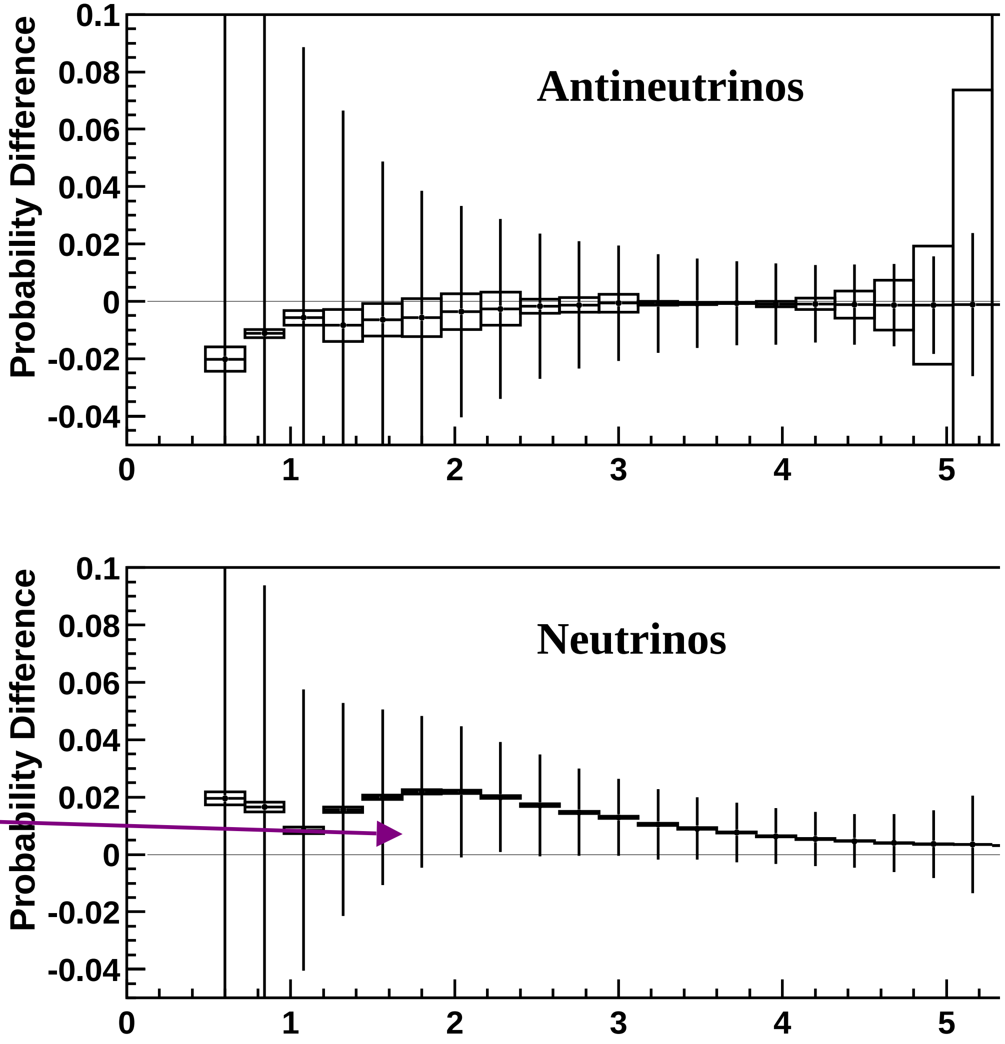
10 kton detector

Direct comparison of oscillation probabilities for neutrinos and antineutrinos



Probability difference

Difference is significant for neutrinos (antineutrinos are matter-suppressed) after evaluation of statistical and systematic errors (5% variation in τ contribution)



Direct measurement of the CP-odd component.

Comparison of direct method with fit

90% C.L. contours for δ_{13}, Δm^2_{12}

A) L=2900 km, E=30 GeV with WSE

B) L=732 km, E=7.5 GeV with WSE

C) L=2900 km, E=30 GeV no WSE

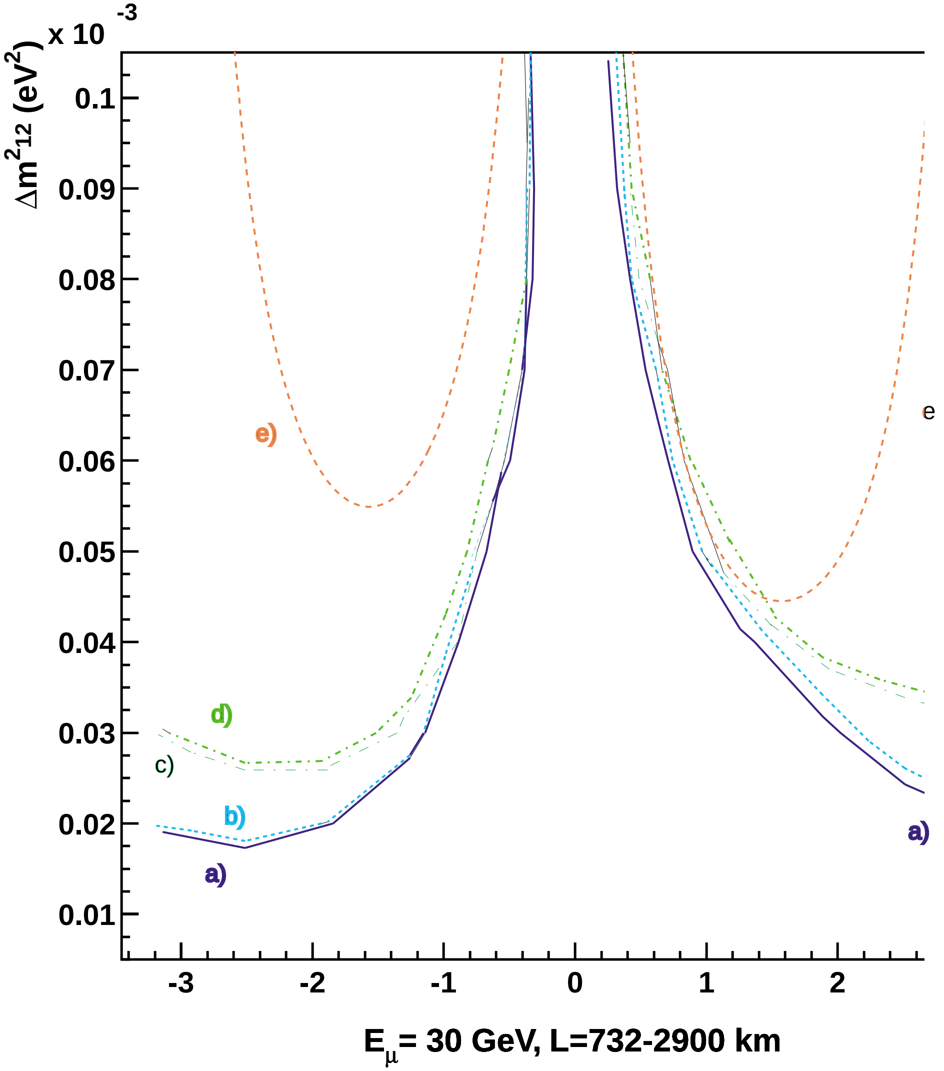
D) L=732 km, E=7.5 GeV no WSE

E) L=732 km, E=5 GeV direct method

E_μ=30 GeV → 2.5*10^{20} decays

E_μ=5 GeV → 10^{21} decays

As expected, for fixed machine power there is no advantage in going to high energy!!



Conclusions

- A direct measurement of T-violation is possible at a neutrino factory using a magnetized, fine-grained detector through the identification of Wrong-Sign Electron events.
- Comparison of oscillation probabilities for neutrinos and antineutrinos is not sensitive to matter effects, and does not require the precise knowledge of oscillation parameters
- To have better electron charge determination, and smaller background from τ decays, the best configuration is a medium-energy, long-baseline beam
- The result is statistically significant with a reasonable choice of parameters, and is not much worse than the MC-based fit
- For a given machine power, CP effect only depends on L/E
- This is an extremely powerful and convincing way to prove the existence of CP violation in the leptonic system.