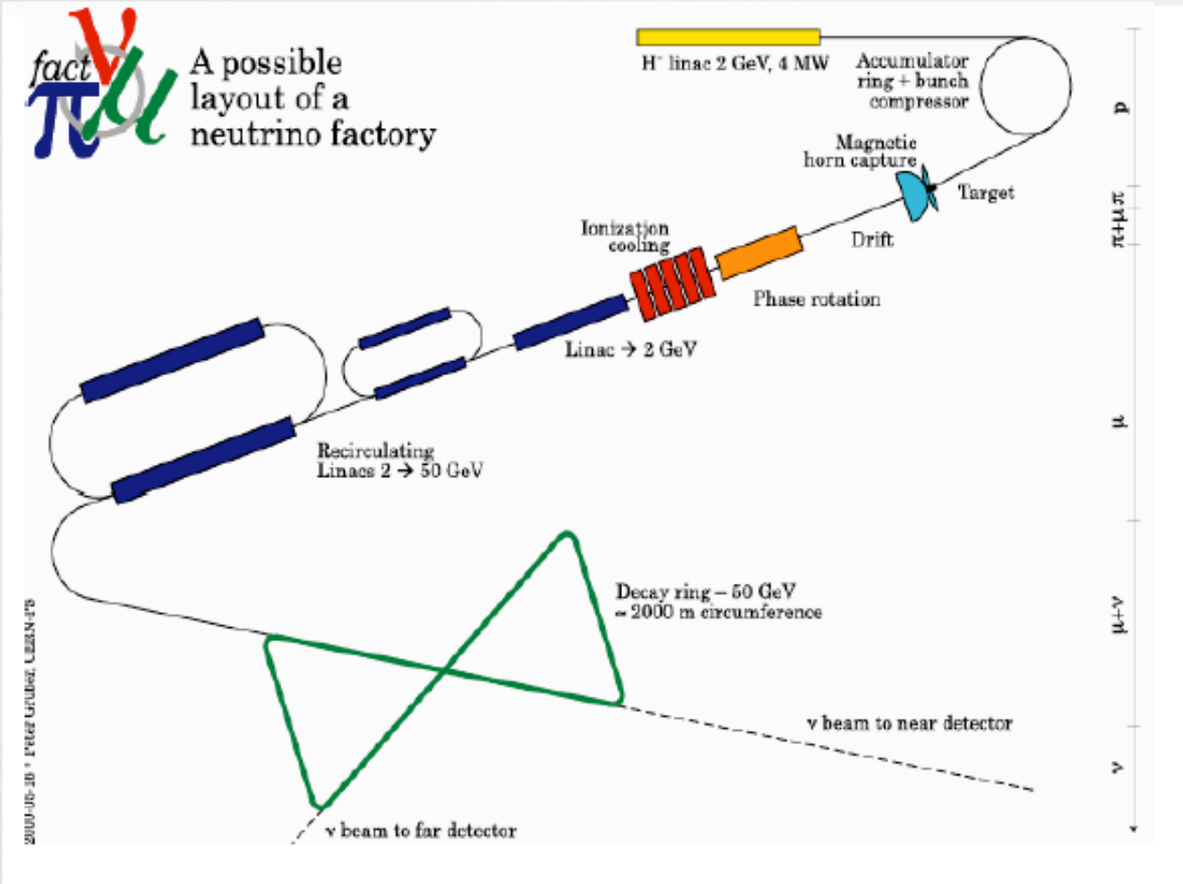
PHYSICS OF THE NEUTRINO FACTORY (AND FRIENDS)



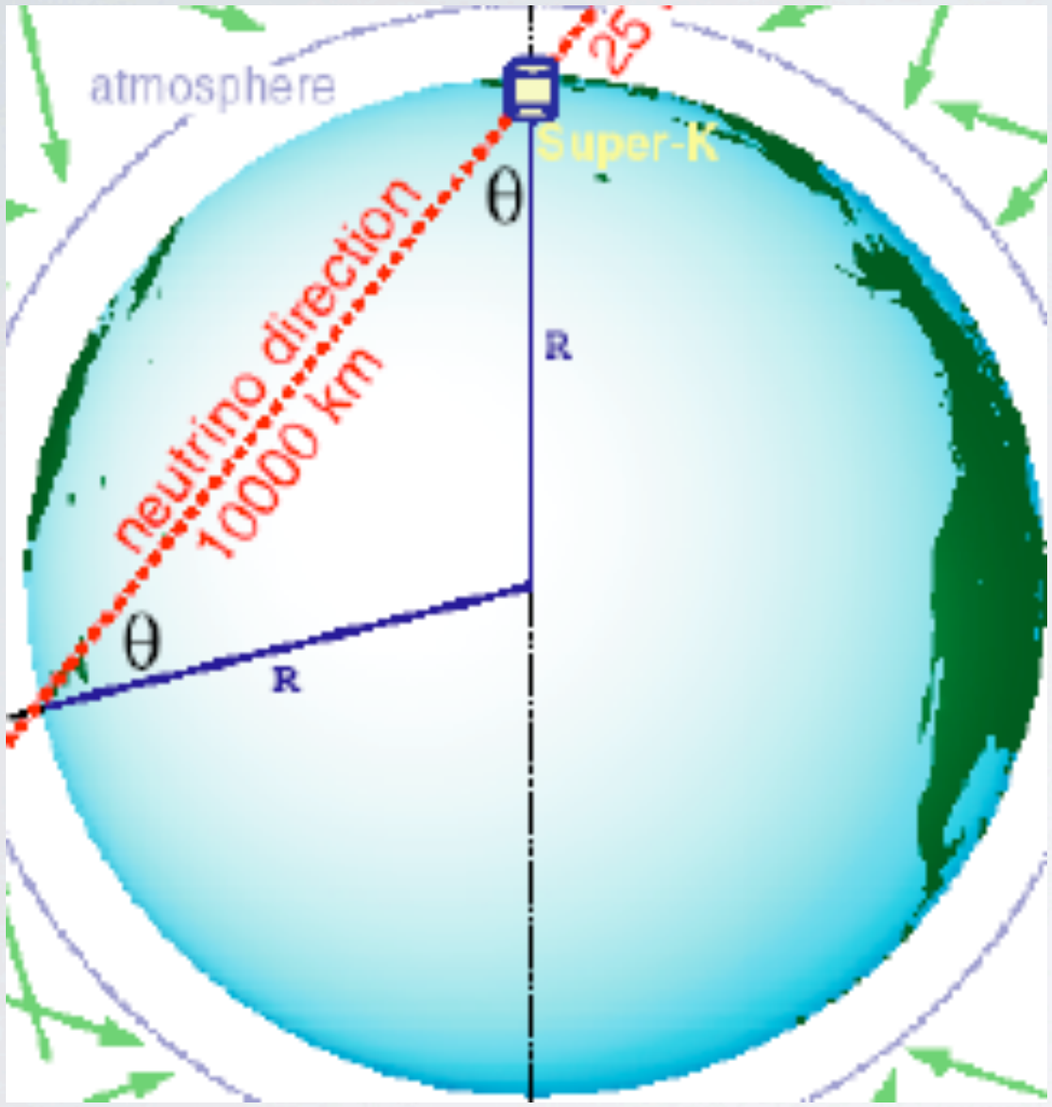
J.J. Gómez Cadenas
IFIC (CSIC-UV)

Lecture II

LECTURE II

- Matter matters
- Degenerate physics
- Design your experiment

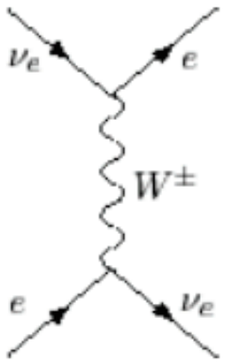
TRAVEL IN MATTER

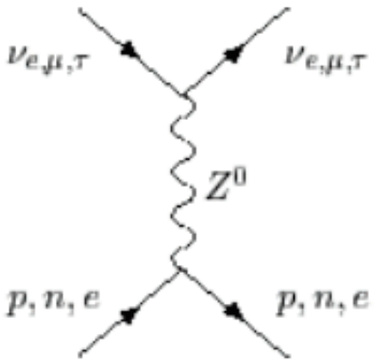


- In a NuF, rates grow with muon energy (flux & cross sections increase with E)
- To work at the oscillation peak one needs long baselines (~5000 km at 10 GeV)
- This implies that the neutrino beam travels through Earth.
- But Earth is less transparent to ν_e than to ν_μ, ν_τ

THE MATTER PARAMETER A

ν_e, ν_μ, ν_τ interact with e, p and n of matter via NC.interactions (Z). Only ν_e interact via (CC) with the electrons of the medium



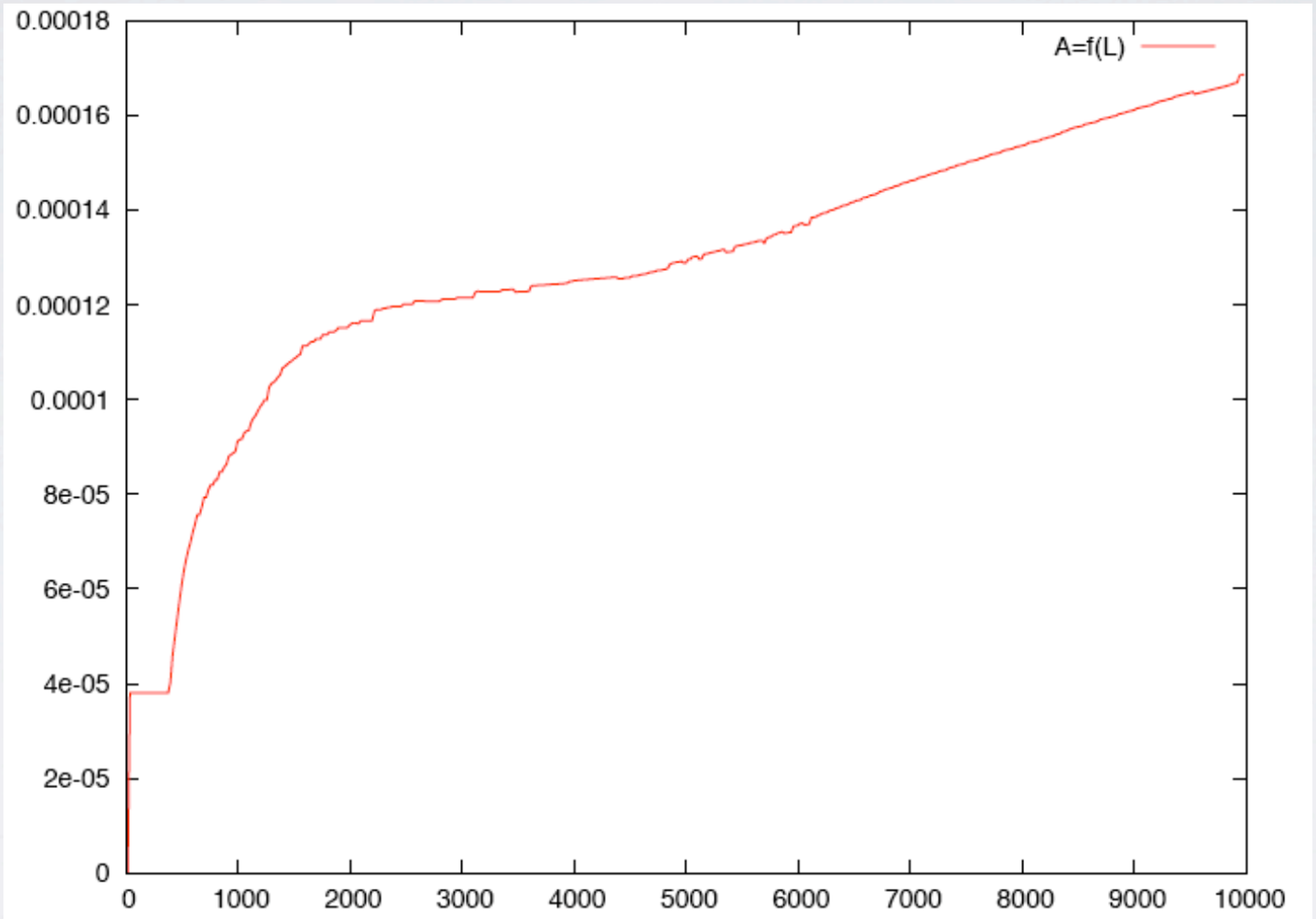


- The fact that ν_e (both neutrinos and antineutrinos) have charged current elastic scattering interactions on the Earth electrons introduce effective "masses" for the electron neutrinos m= ± 2EA, where A is the matter parameter

MATTER IMPORTANT AT LARGE L

$A = \sqrt{2} G_F n_e \rightarrow n_e$ is electron number density

$\frac{eV^2}{GeV}$



km

A increases with L → Matter effects important at large L

$$P_{atm} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{1.267\Delta m^2_{atm}L}{E}\right) \rightarrow s^2_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta_{23}L}{2}\right), \quad \Delta_{23} = \frac{2.534\Delta m^2_{atm}}{E}$$

$$P_{sun} = \cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\left(\frac{1.267\Delta m^2_{sol}L}{E}\right) \rightarrow c^2_{23}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta_{12}L}{2}\right), \quad \Delta_{12} = \frac{2.534\Delta m^2_{sol}}{E}$$

$$P_{\text{int}} = J\cos\left(\pm\delta - \frac{1.267\Delta m^2_{atm}L}{E}\right)\left(\frac{1.267\Delta m^2_{sol}L}{E}\right)\sin\left(\frac{1.267\Delta m^2_{atm}L}{E}\right) \rightarrow J\left(\frac{\Delta_{12}L}{2}\right)\sin\left(\frac{\Delta_{23}L}{2}\right)\cos\left(\pm\delta - \frac{\Delta_{23}L}{2}\right)$$

$Matter :\rightarrow B_{\mp} = \left|A \mp \Delta_{23}\right|$

$A \rightarrow 0 \Rightarrow B_{\mp} = \Delta_{23}$

$A \geq \Delta_{23} \Rightarrow B_{\mp}$ is different for ν and $\bar{\nu}$: "Fake CP violation effect"

Matter effects can be described by the following (golden) formula:

A $\rightarrow \Delta_{12}$: Effective neutrino mass shorten solar oscillation

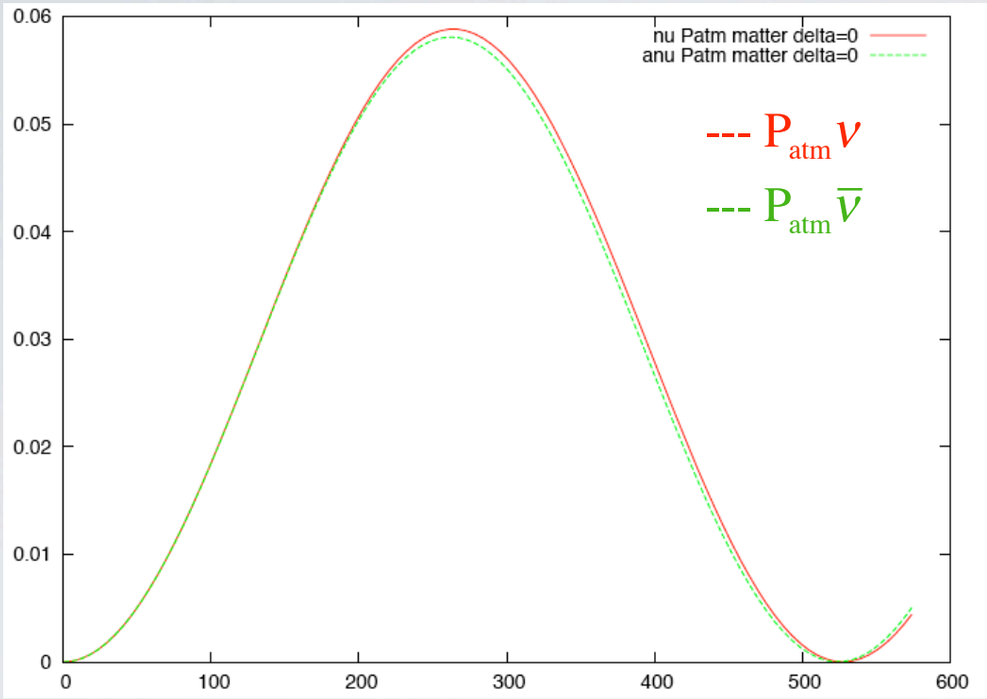
$B_{\mp} \rightarrow \Delta_{23}$: Matter distinguishes between ν and $\bar{\nu}$

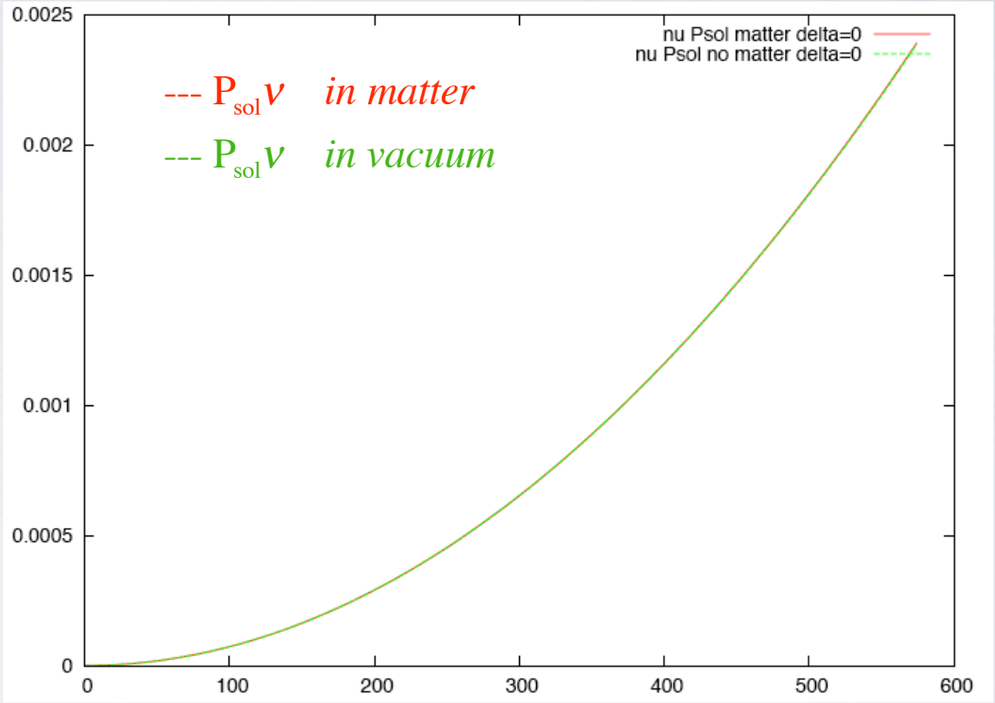
$$P_{atm} = s^2_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{23}}{B_{\mp}}\right)^2\sin^2\left(\frac{B_{\mp}L}{2}\right) \rightarrow P_{atm} \text{ is now different for } \nu \text{ and } \bar{\nu}$$

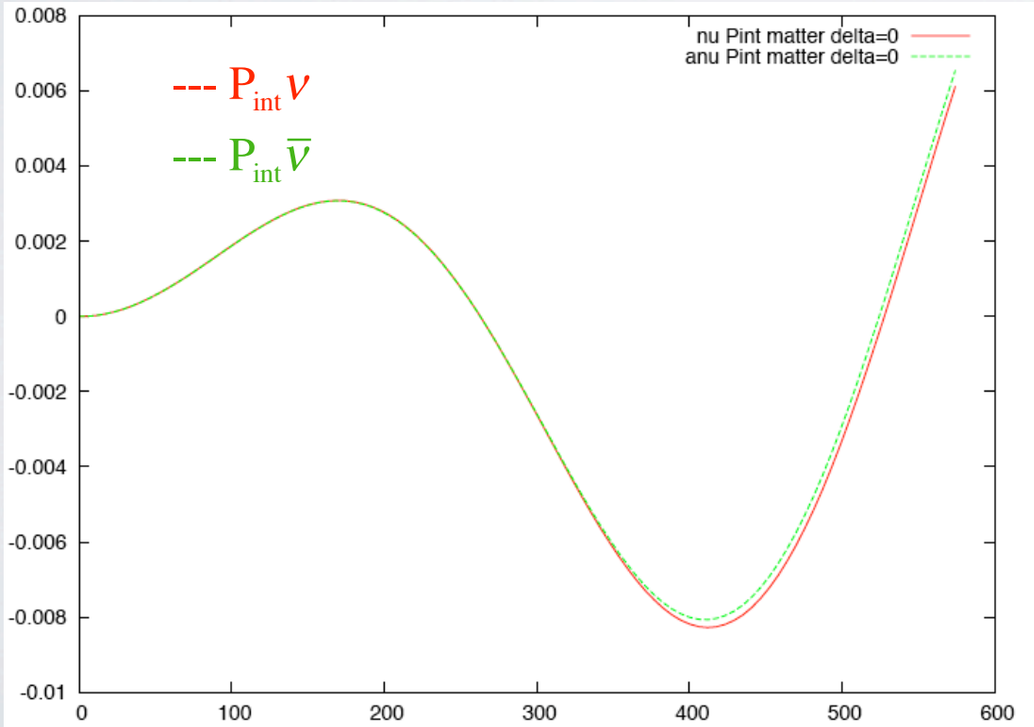
$$P_{sun} = c^2_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\left(\frac{AL}{2}\right) \rightarrow P_{sol} \text{ amplitude controlled by A not by } \Delta_{12}$$

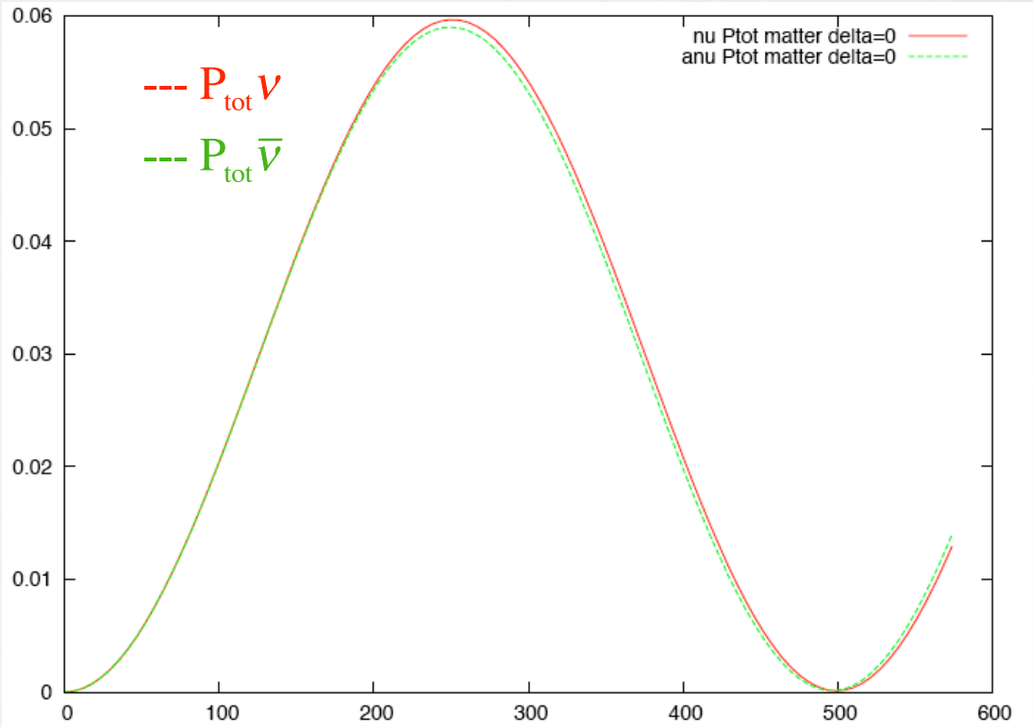
$$P_{\text{int}} = J\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{23}}{B_{\mp}}\right)\sin\left(\frac{AL}{2}\right)\sin\left(\frac{B_{\mp}L}{2}\right)\cos\left(\pm\delta - \frac{\Delta_{23}L}{2}\right) \rightarrow \text{Extra "fake" CP violation in } P_{\text{int}}$$

L=300 KM, NEGLIGIBLE EFFECT

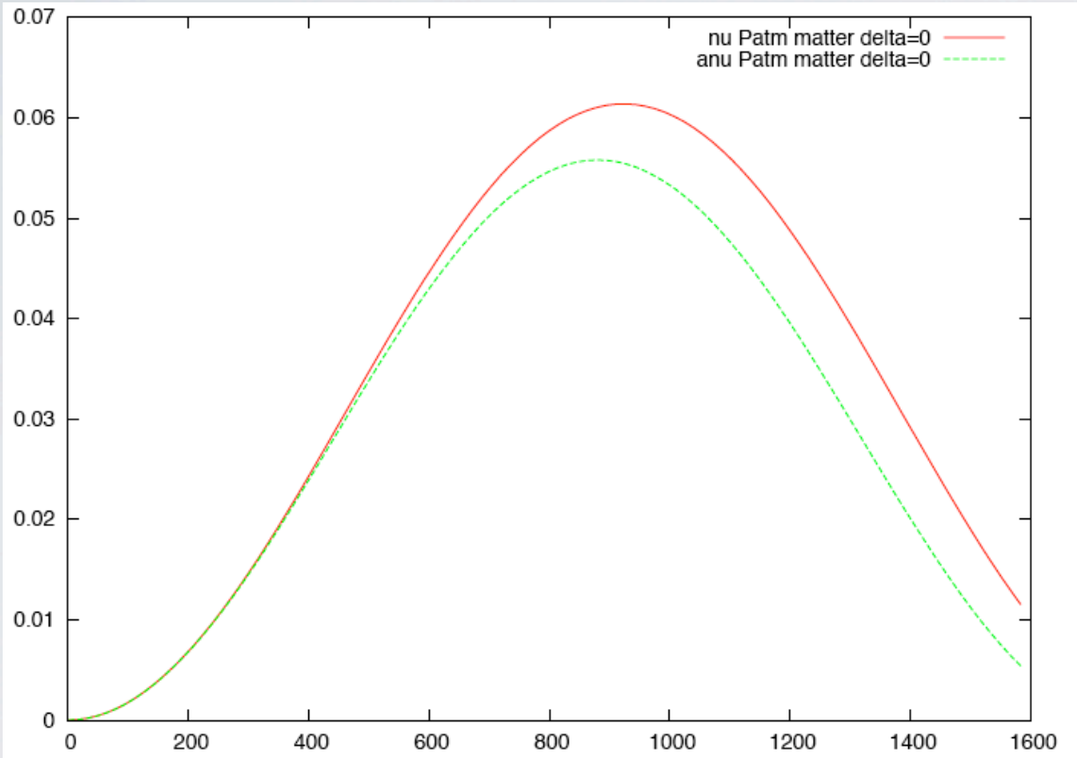


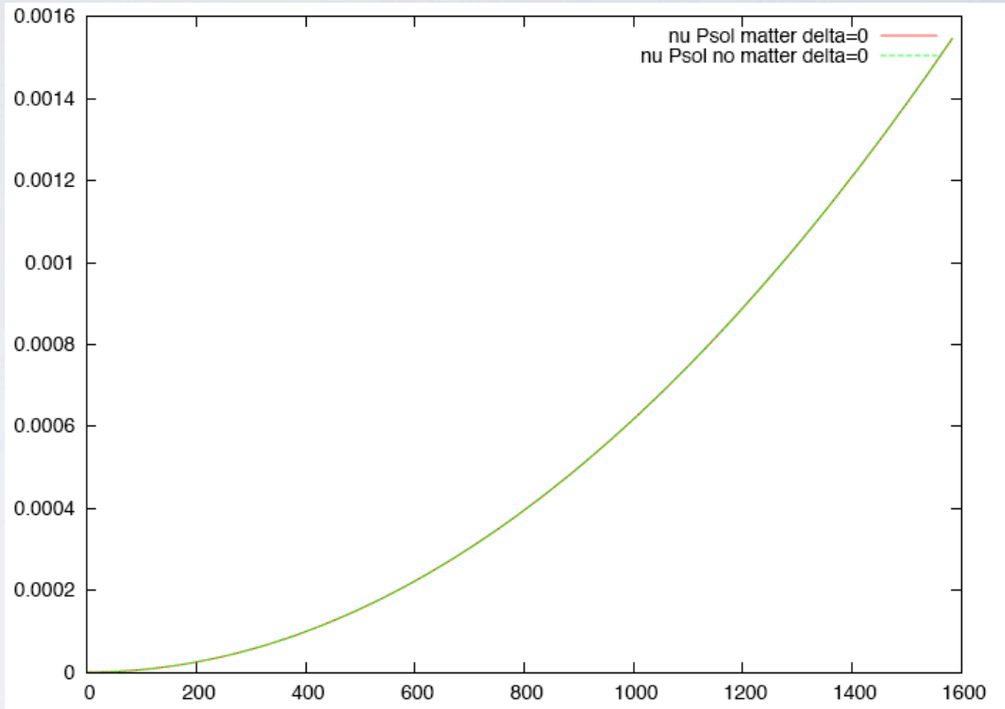


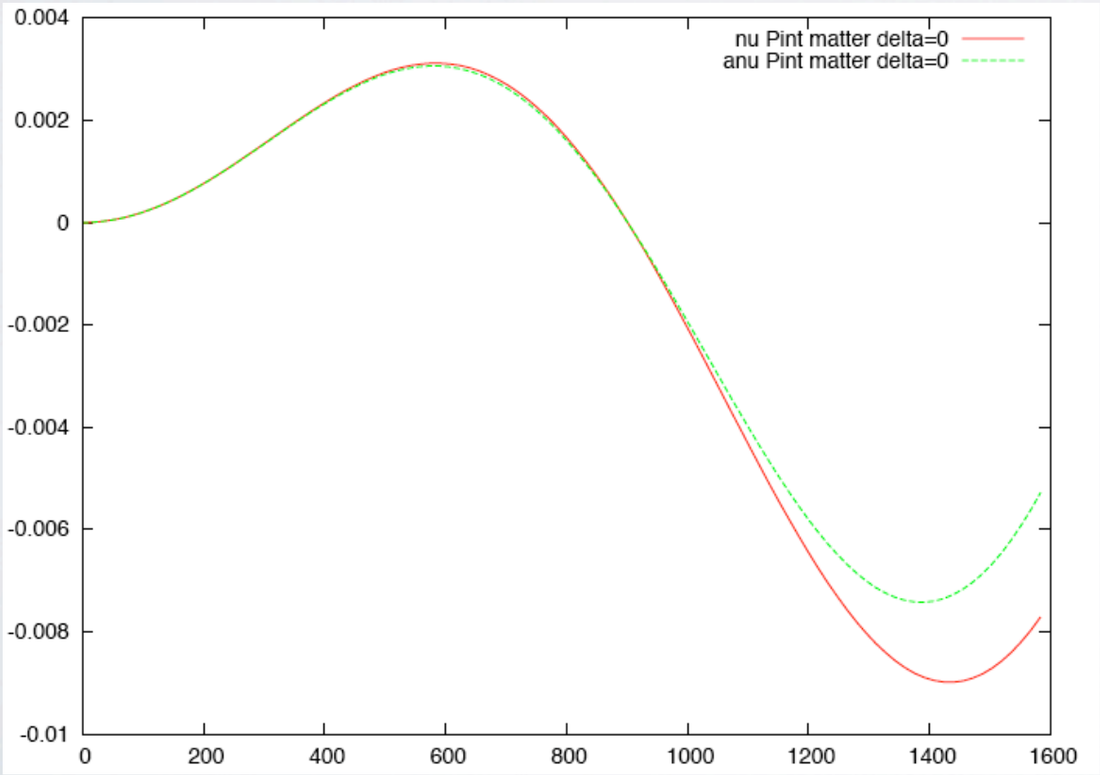


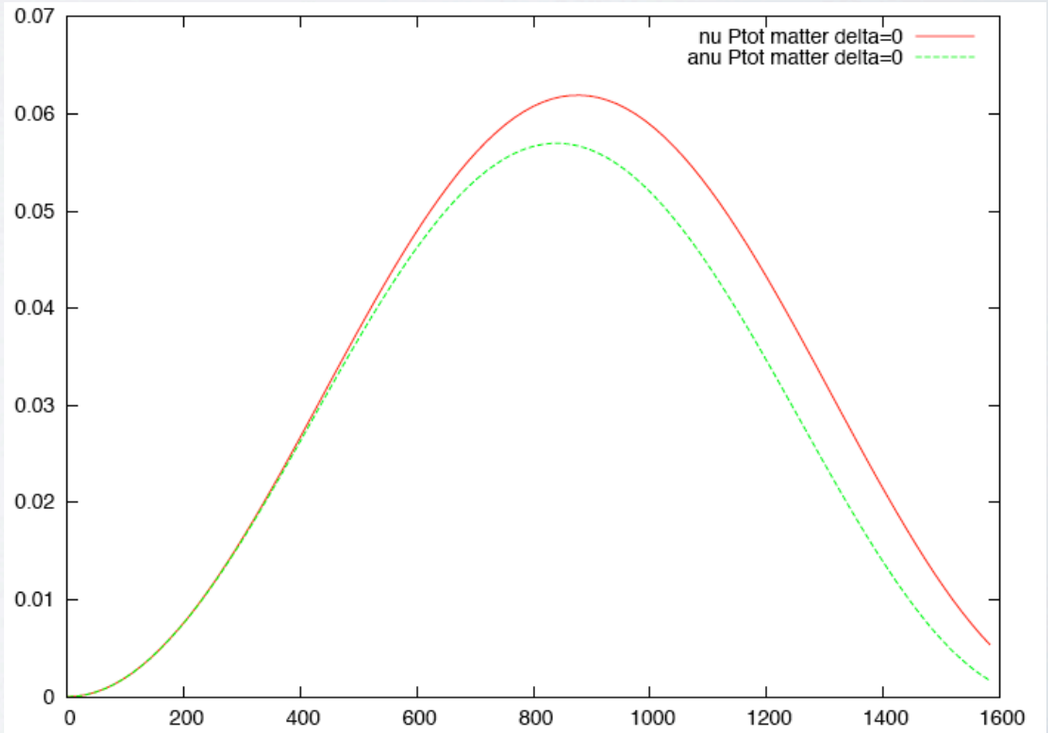


L=1000 KM, ATM TERM SEES EFFECT

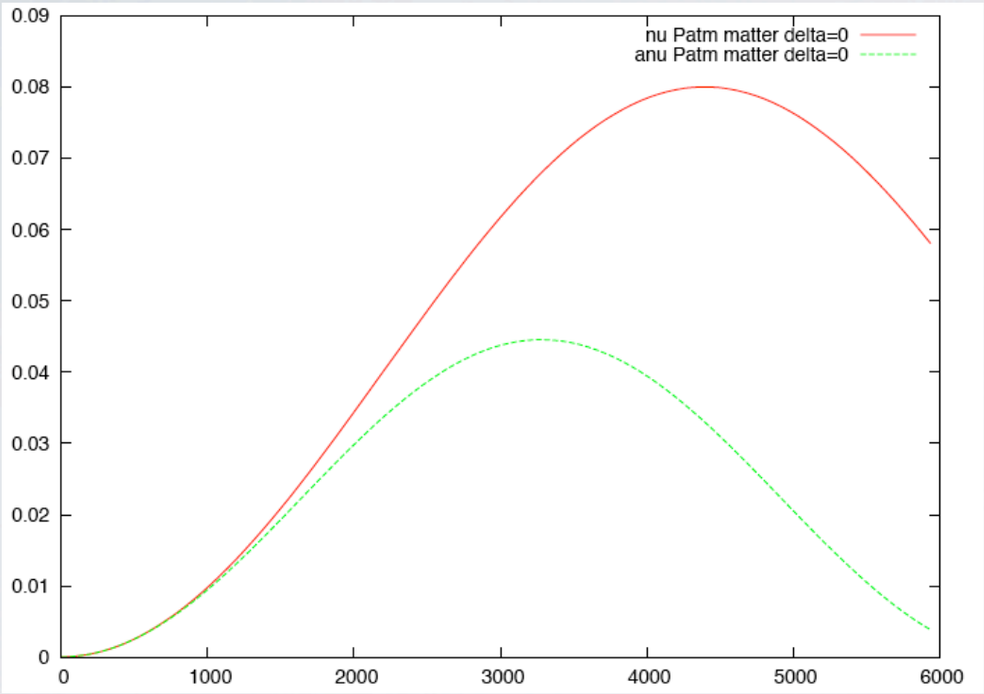


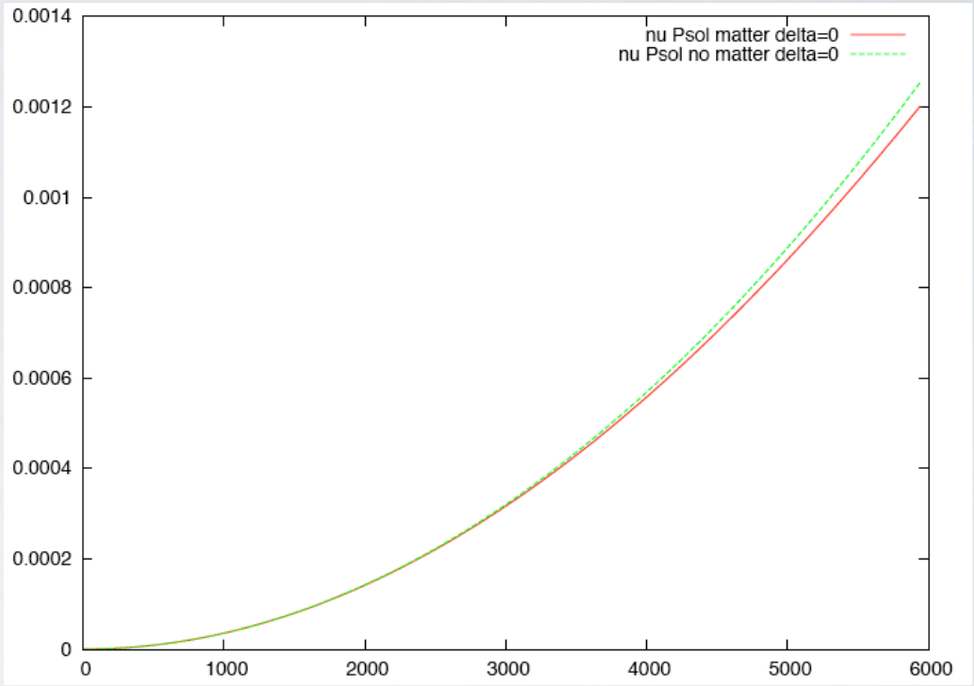


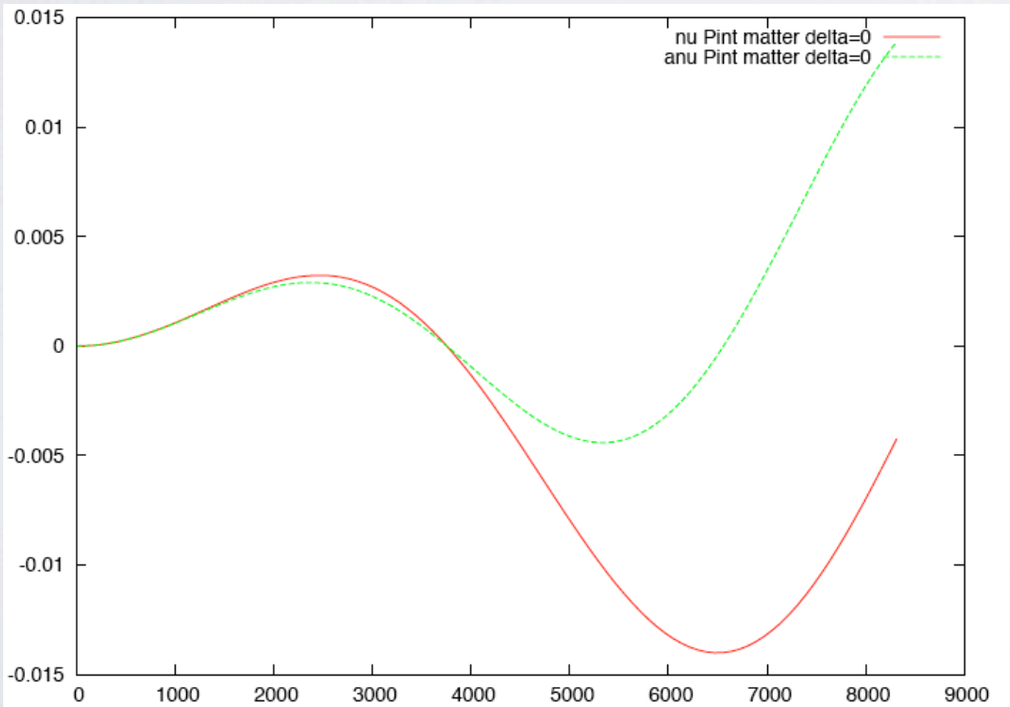


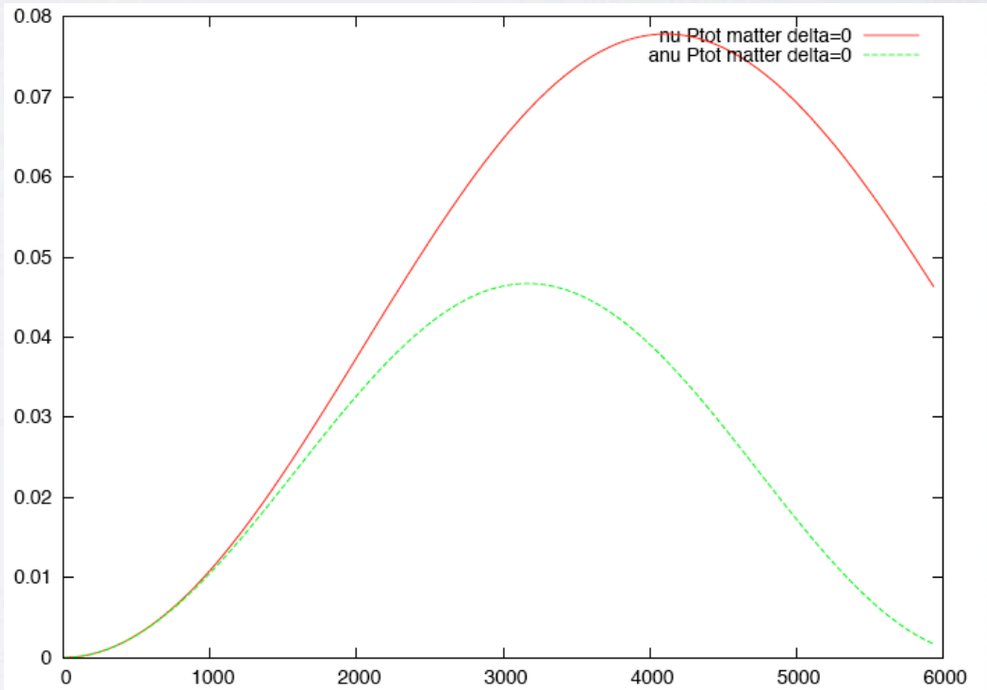


L=3000 KM STRONG ATM EFFECT

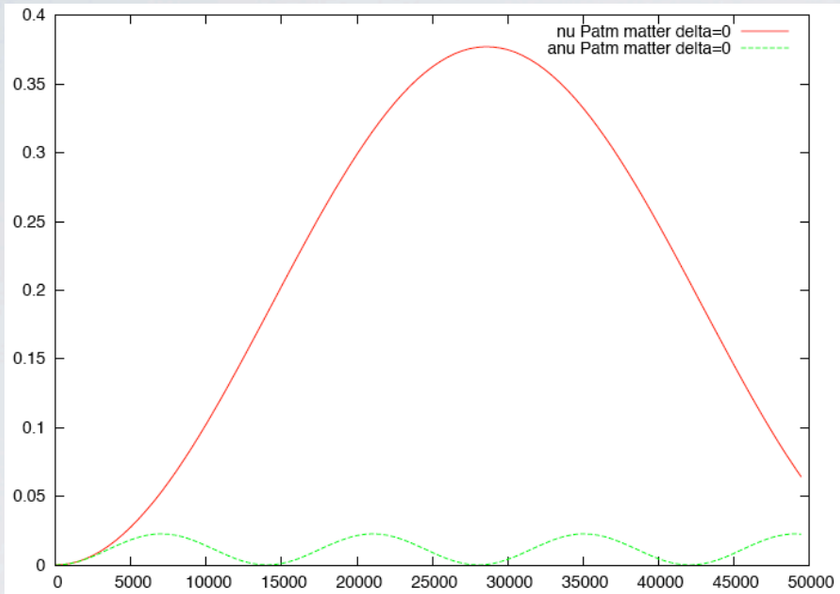


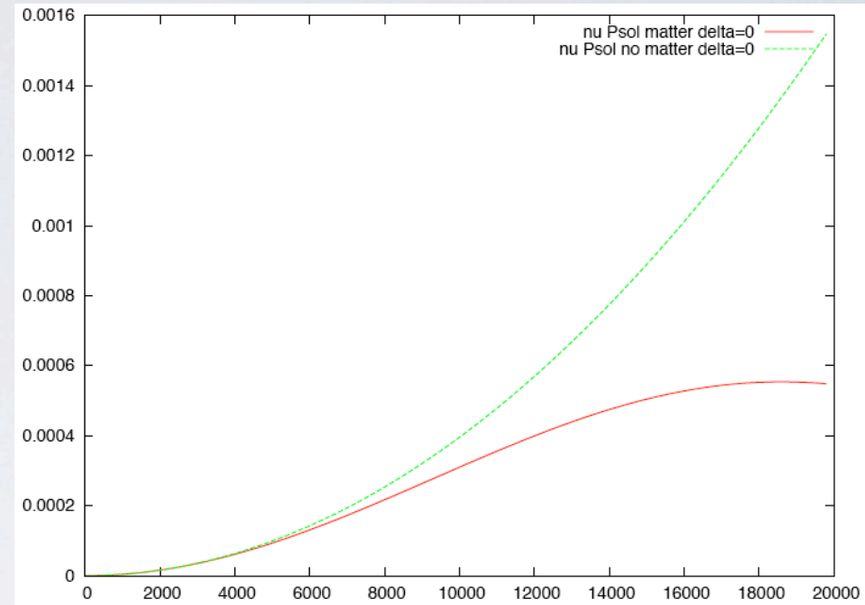


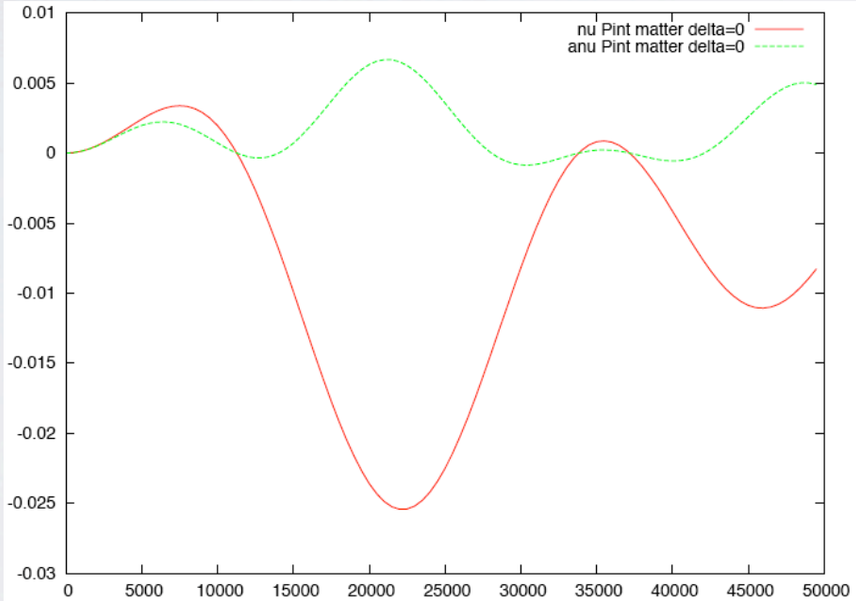


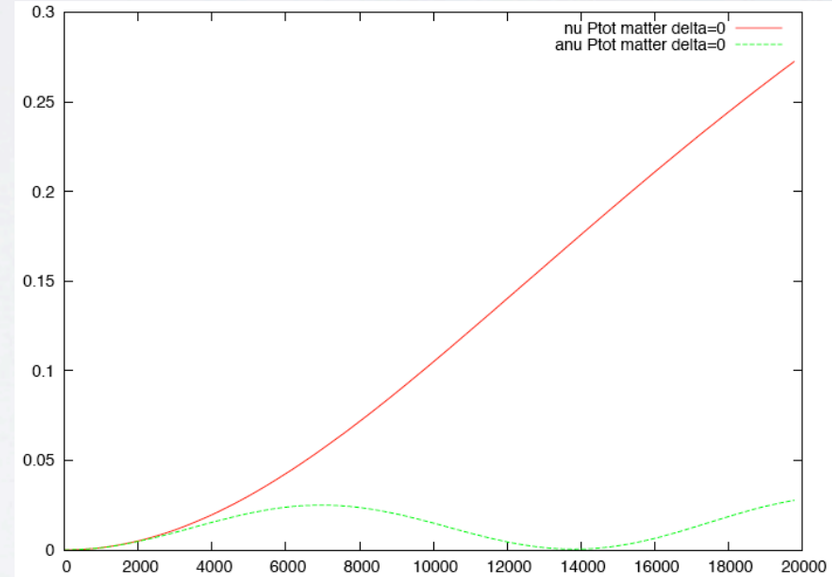


L=10,000 KM ALL IS MATTER



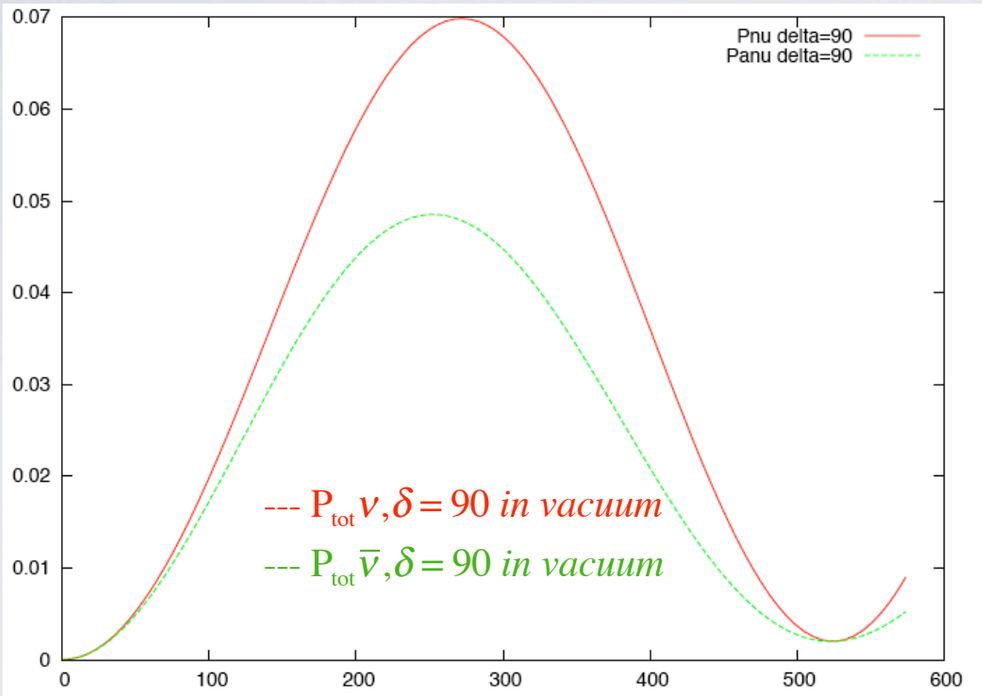


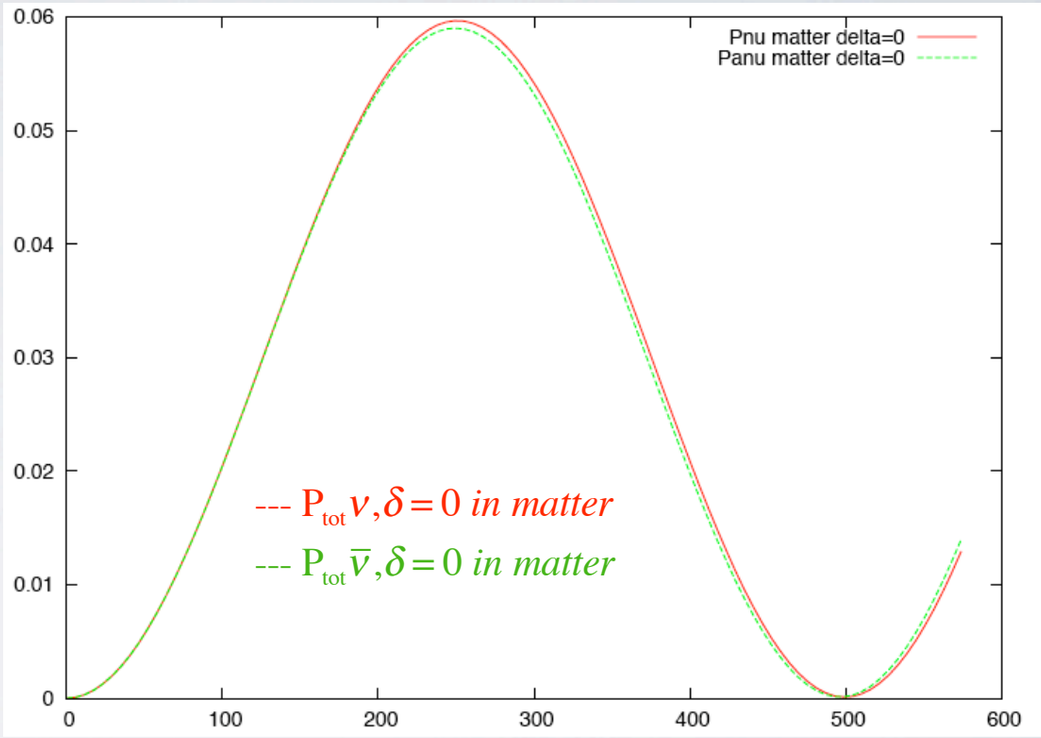


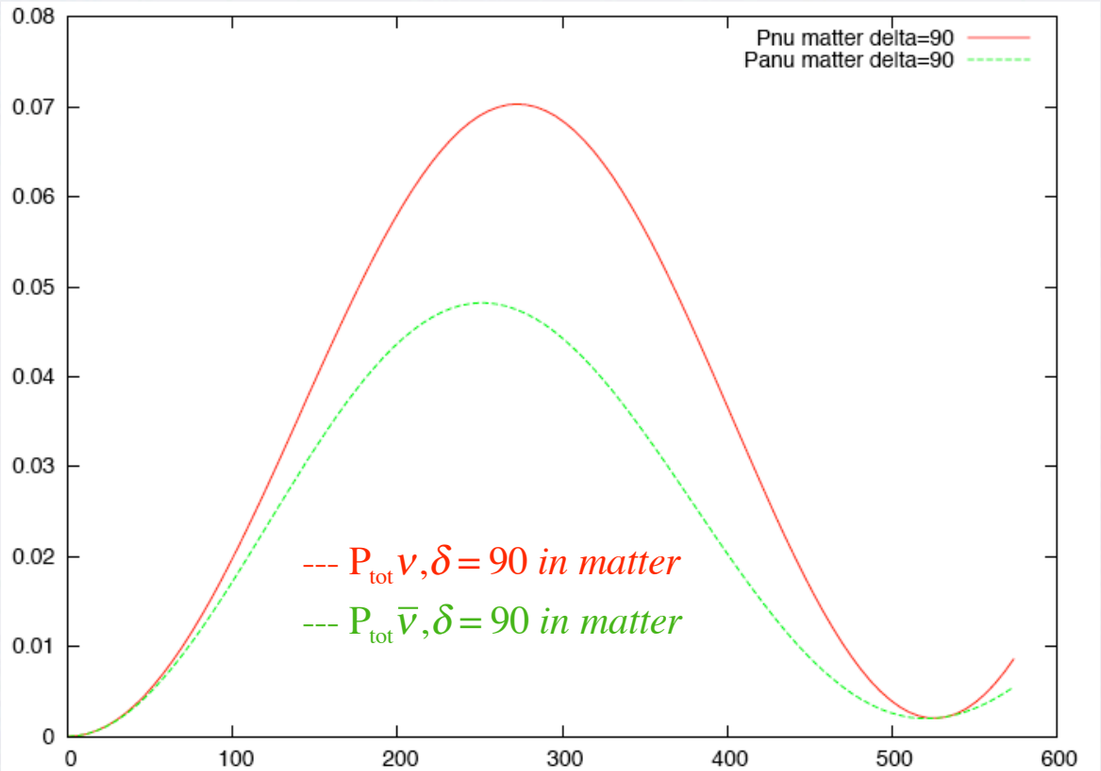


- At L=10000 Km (E=30GeV) matter effects are also important for solar term and will mask completely any oscillation effect

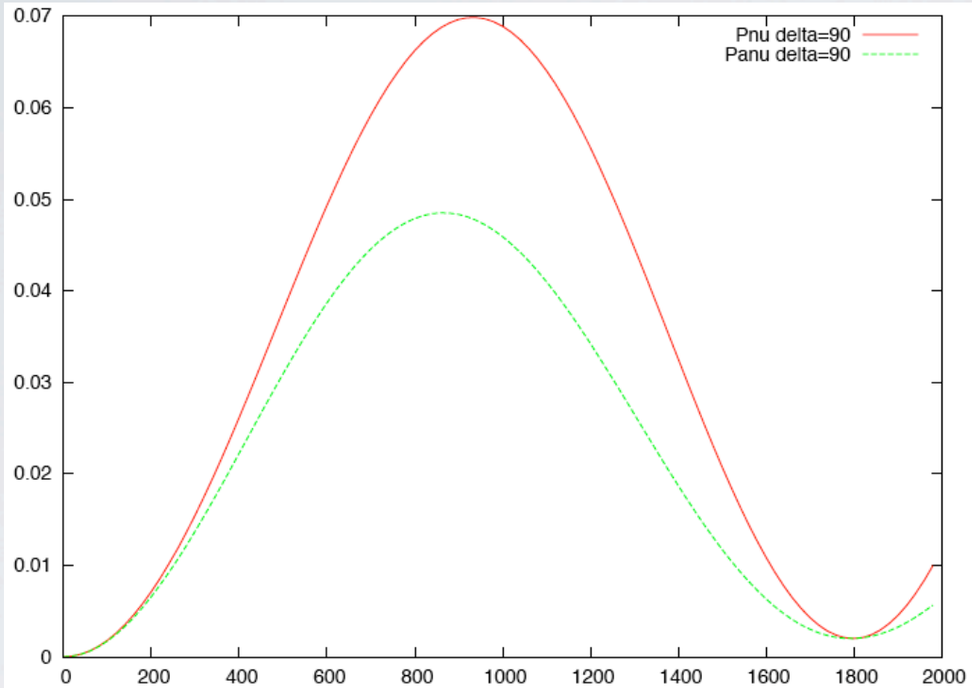
L=300 KM NO FAKE CP

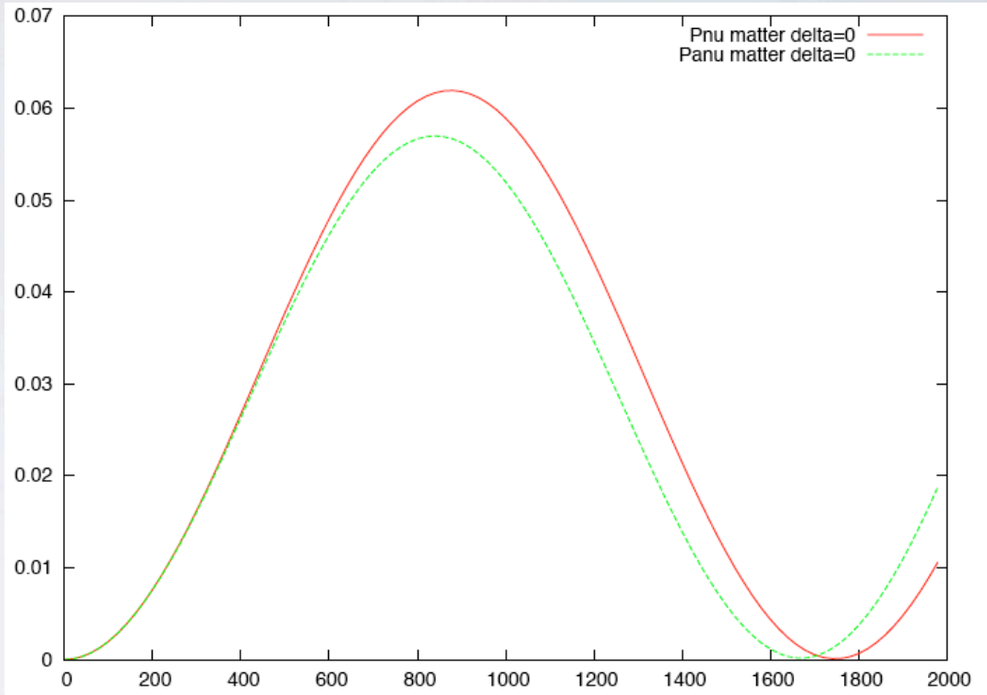


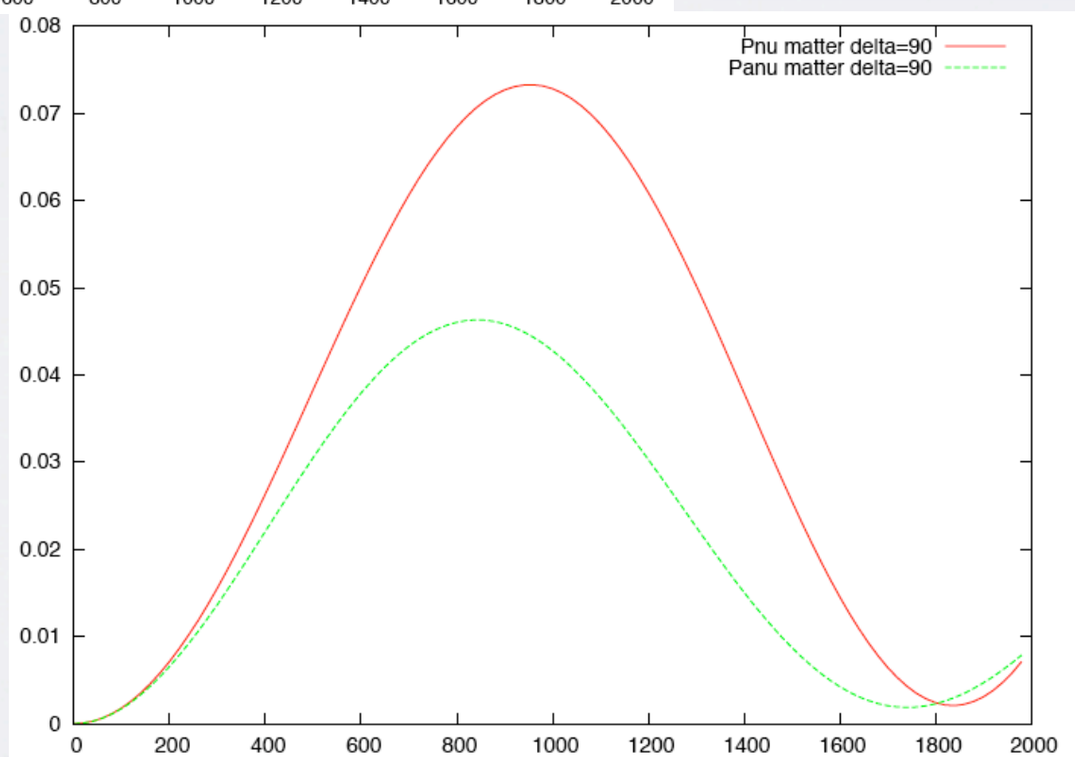




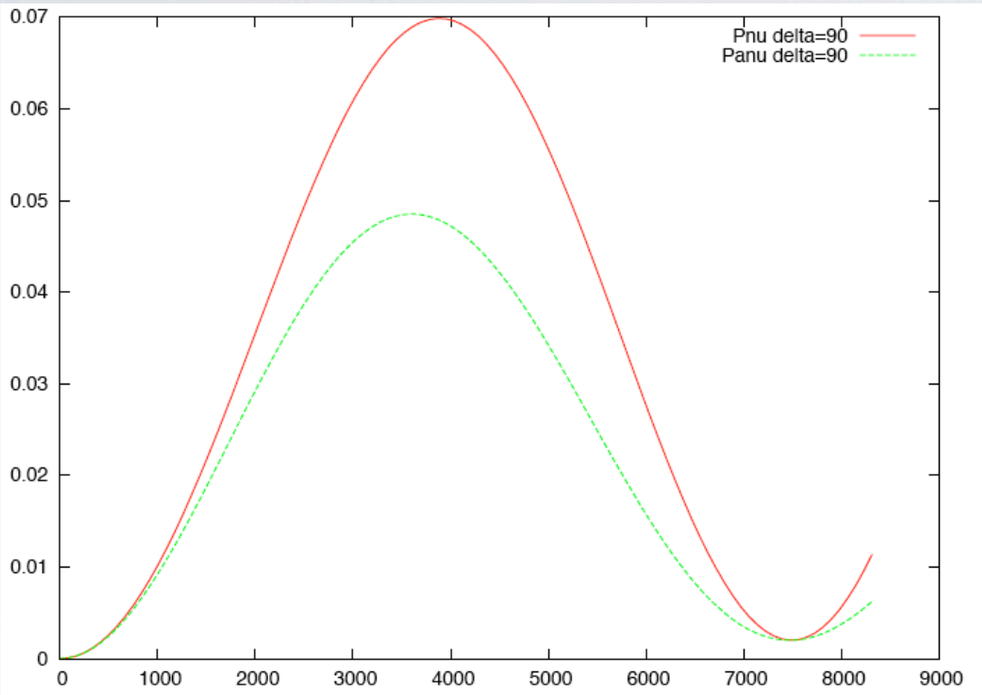
L=1000 KM, TRUE CP LARGER THAN MATTER CP

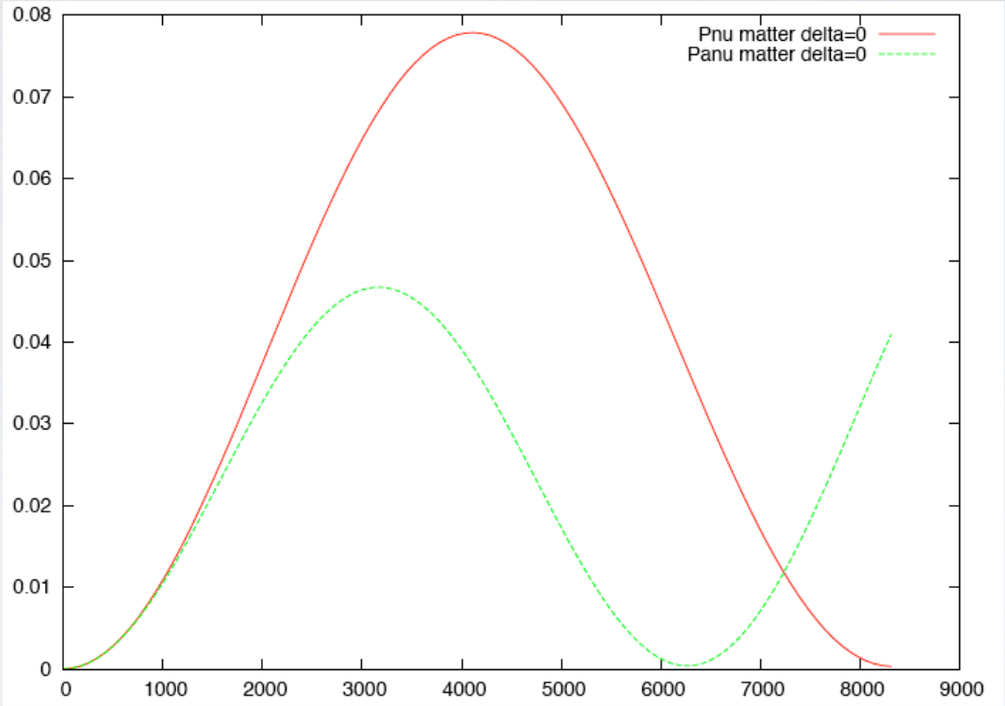


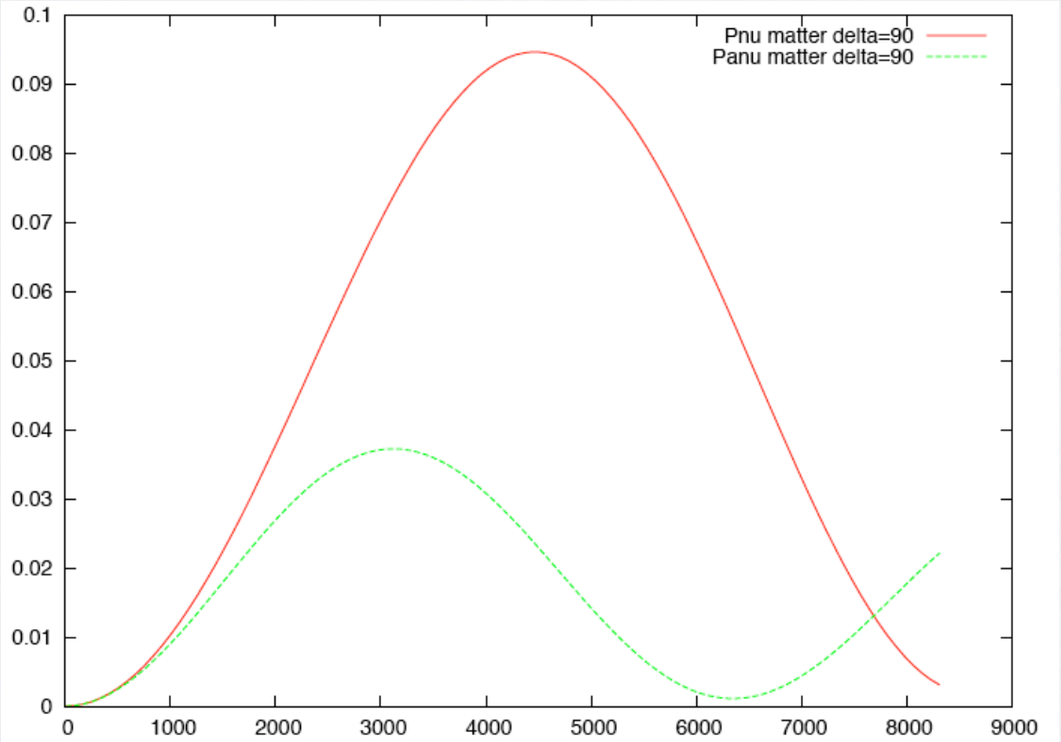




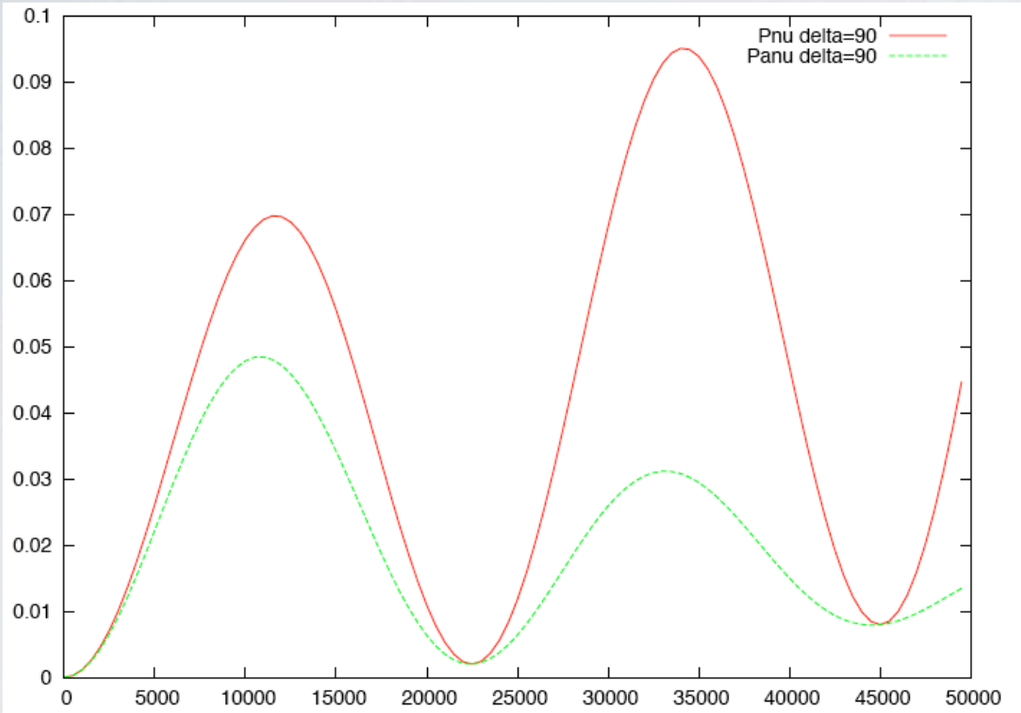
L=3500 KM, TRUE CP SAME ORDER THAN MATTER CP

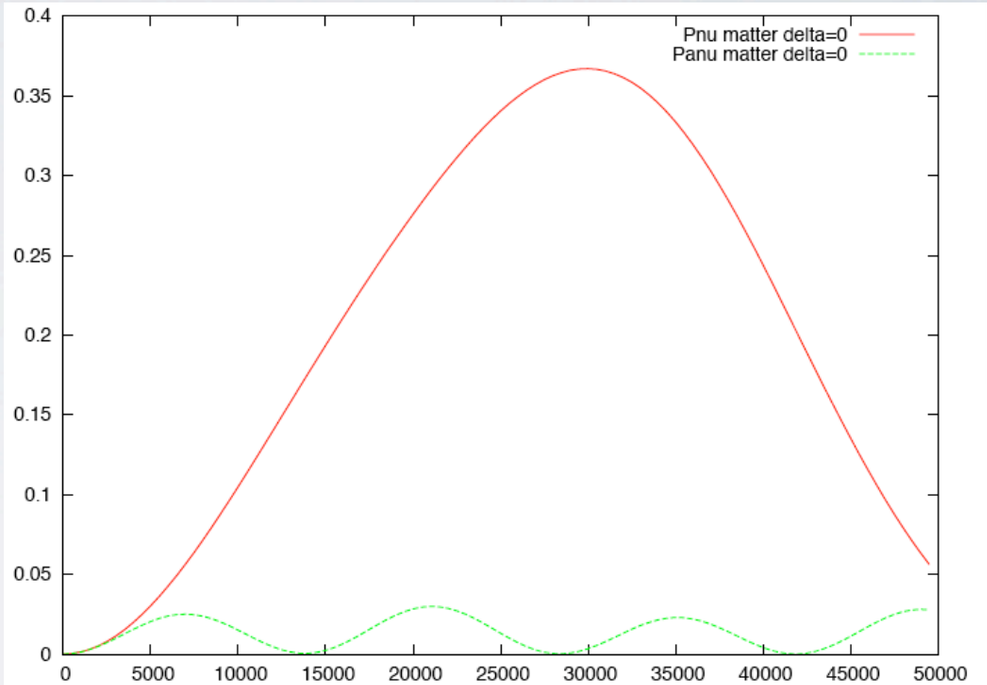


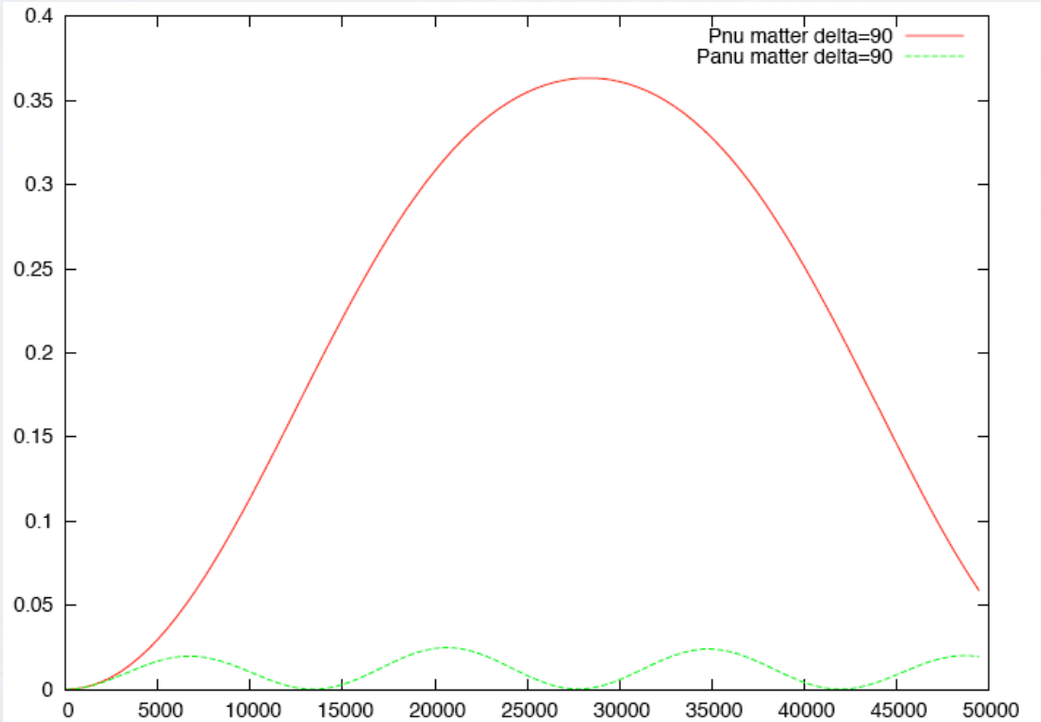




L=10,000 KM, TRUE CP MUCH SMALLER THAN MATTER CP

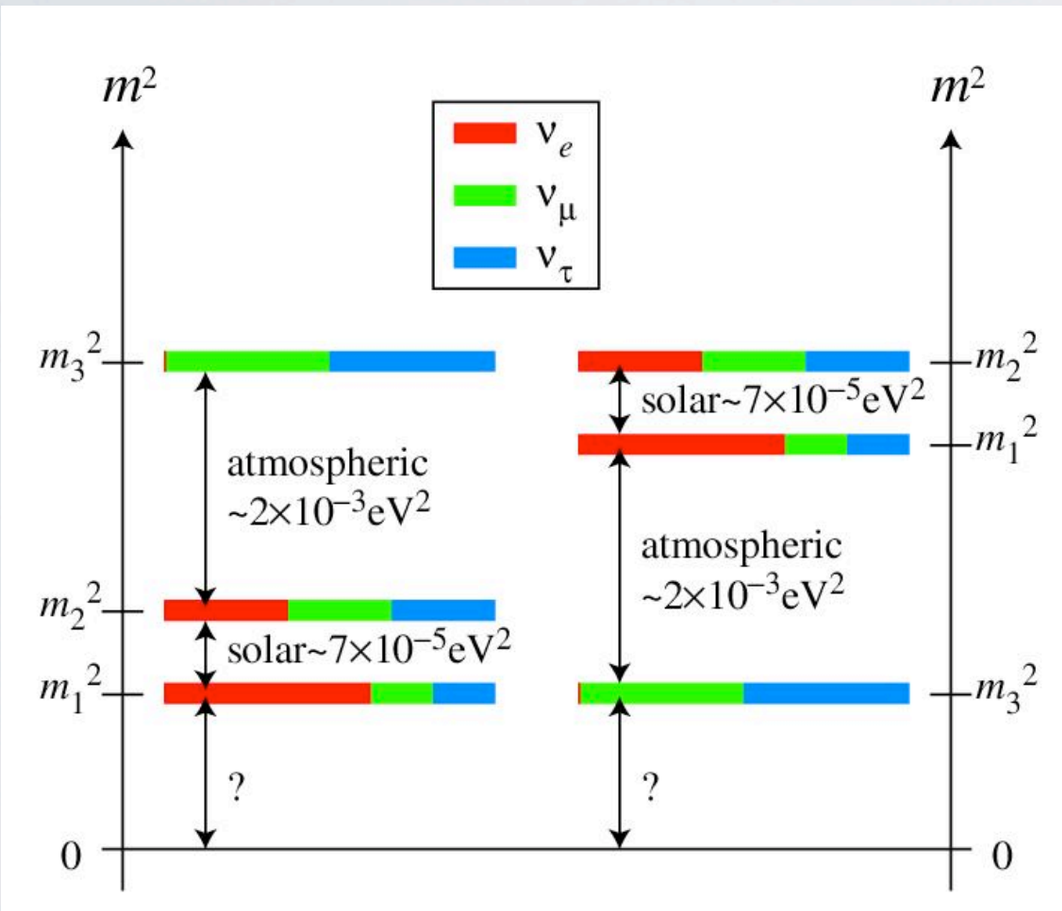






MEASURING THE SIGN OF MATTER

$$Matter :\rightarrow B_{\mp} = \left| A \mp \Delta_{23} \right|$$

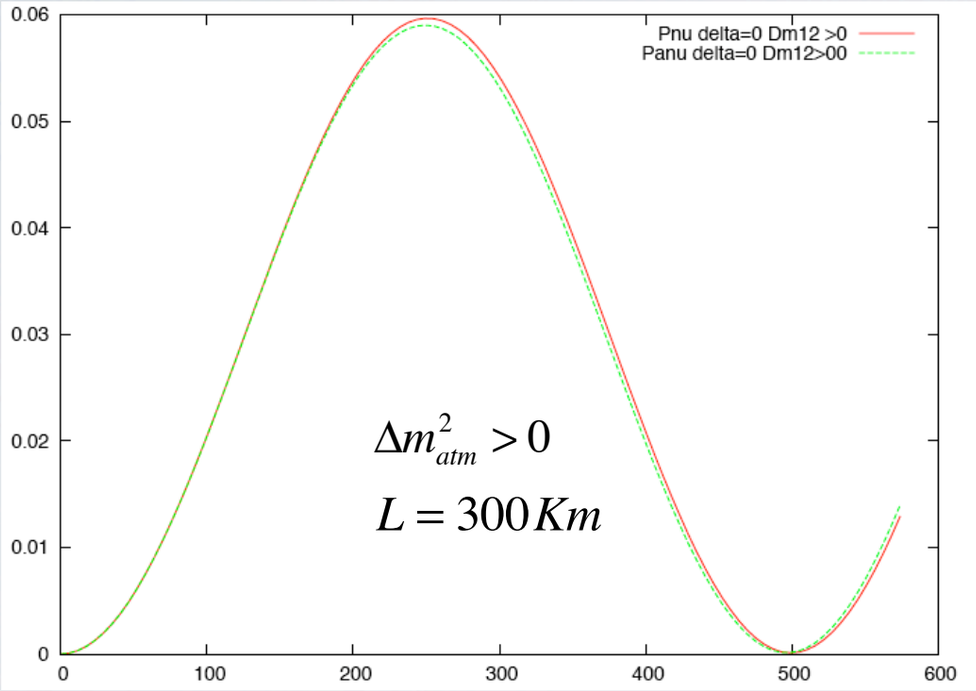


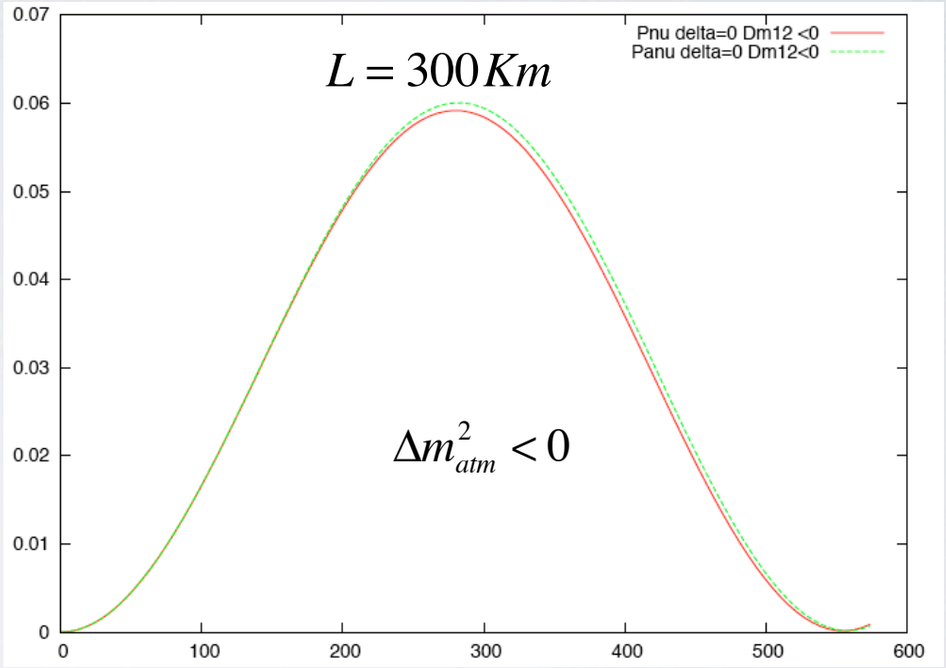
- The bad news: Matter effects are large at large distances. For a high energy neutrino factory one is prevented to go to the oscillation peak and has to work in the "lineal region" where one is less sensitive to ACP.

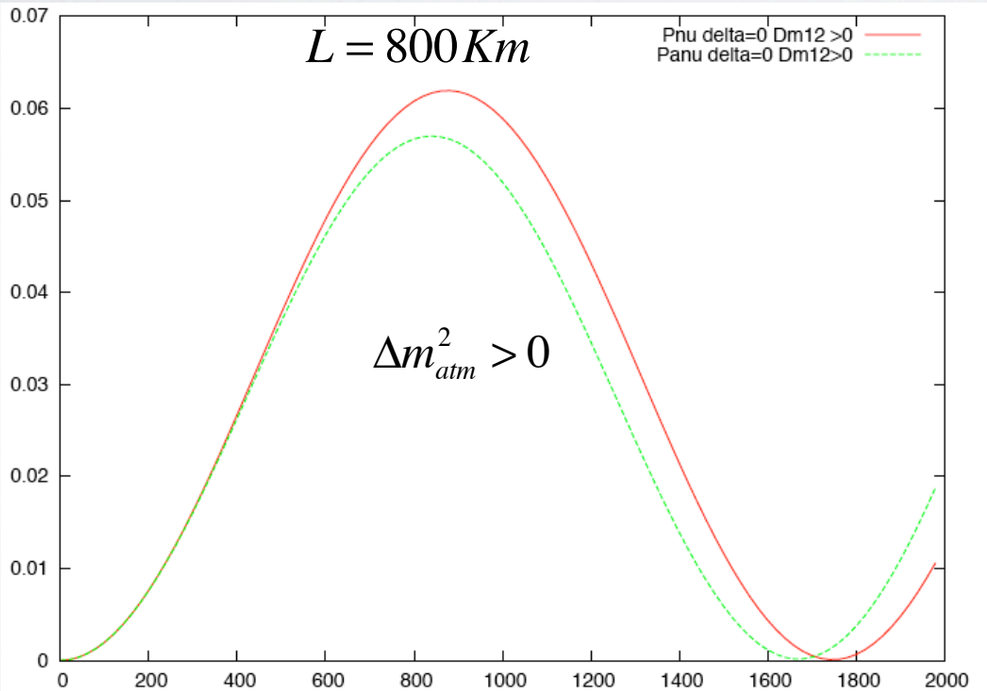
- The good news: Because matter effects are large, one can use them to find out the mass hierarchy, that is the so-called, "sign of matter".

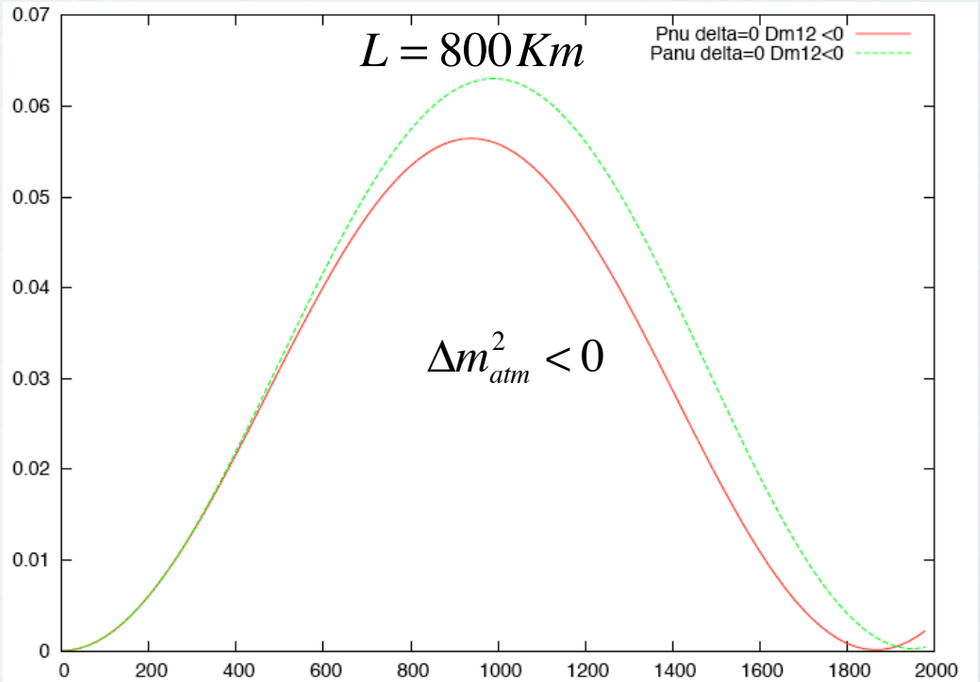
- Notice that B changes sign depending on whether the sign of matter is "positive" or negative".

MEASURING THE SIGN OF MATTER

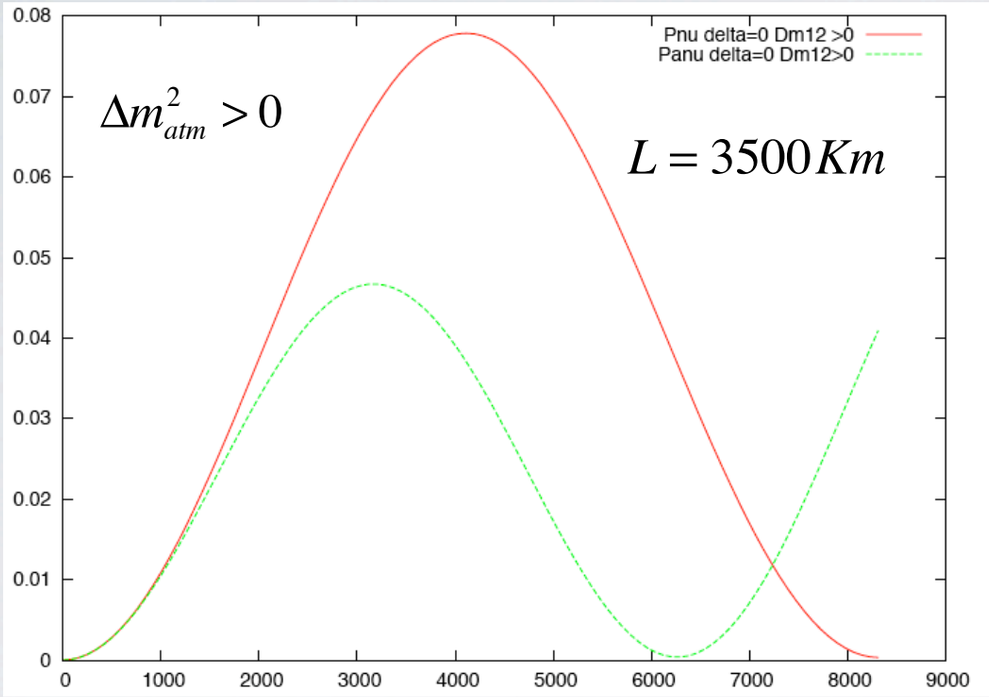


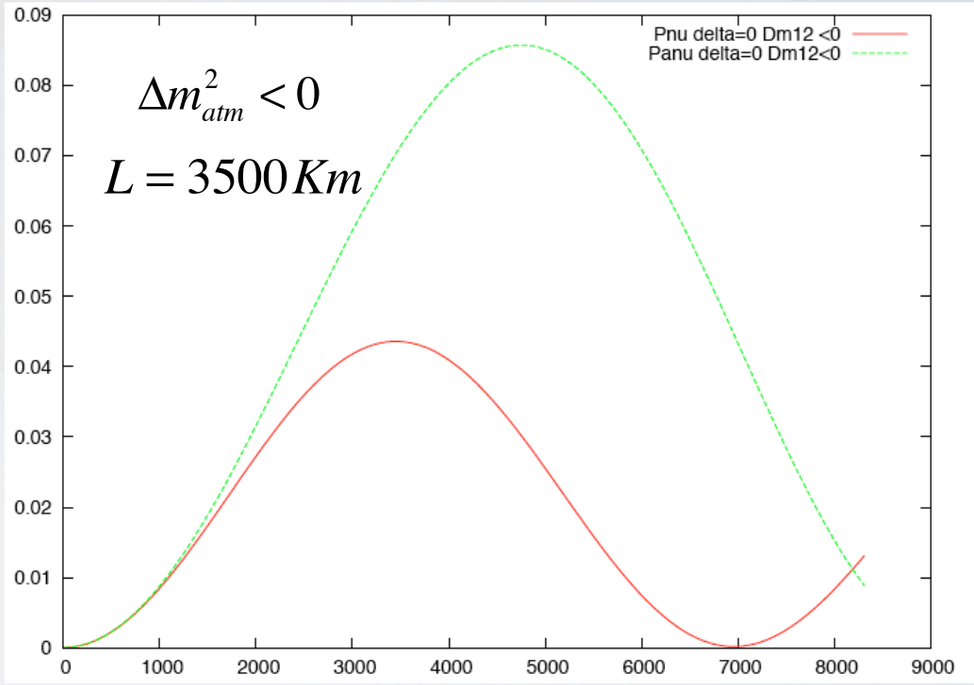


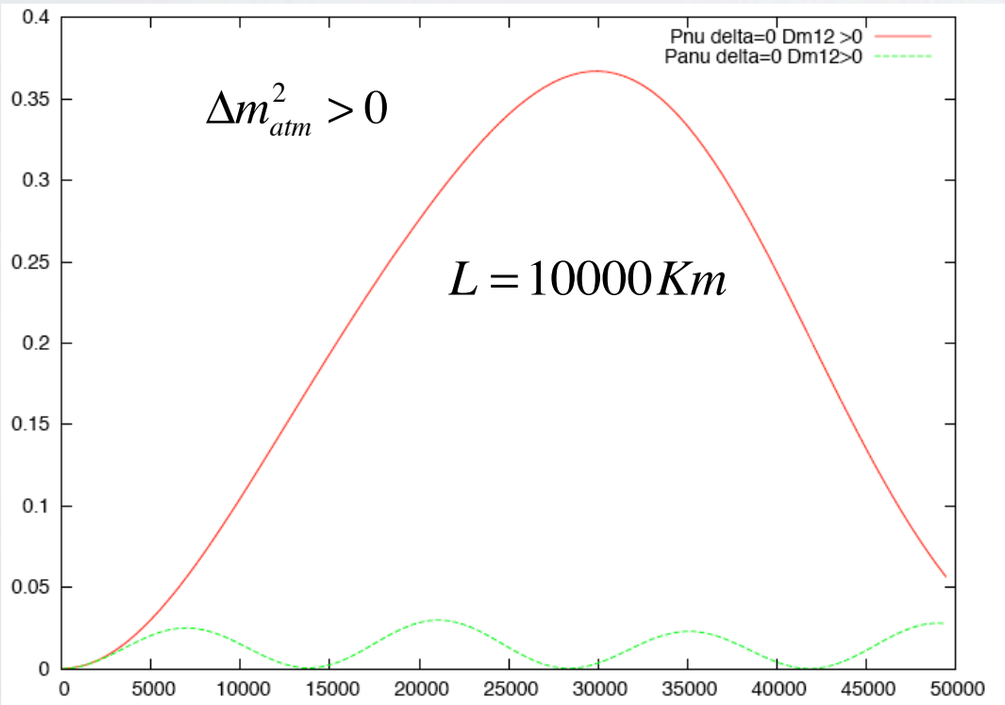


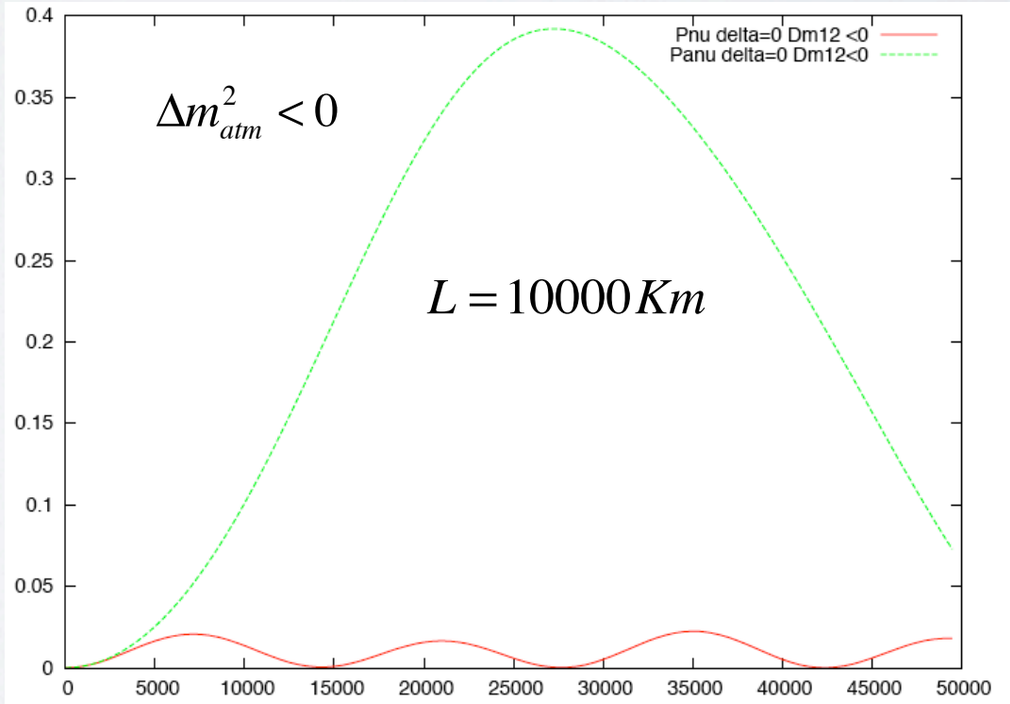


MEASURING THE SIGN OF MATTER









HOMEWORK

- You are the owner of a tunable beta-beam facility.
- Choose a neutrino beam energy
- Choose baseline
- Choose detector technology (explain your reasons)
- Explain your physics program
- Repeat the game for a tunable neutrino-factory.
- Compare both facilities
- Since matter matters. What is your criteria now to choose a baseline?