

fact π μ

A possible layout of a neutrino factory

H⁺ linac 2 GeV, 4 MW

Accumulator ring + bunch compressor

Magnetic horn capture

Target

Drift

Phase rotation

Ionization cooling

Linac → 2 GeV

Recirculating Linacs 2 → 50 GeV

Decay ring – 50 GeV
~ 2000 m circumference

ν beam to near detector

ν beam to far detector

μ + μ π

μ + ν

ν

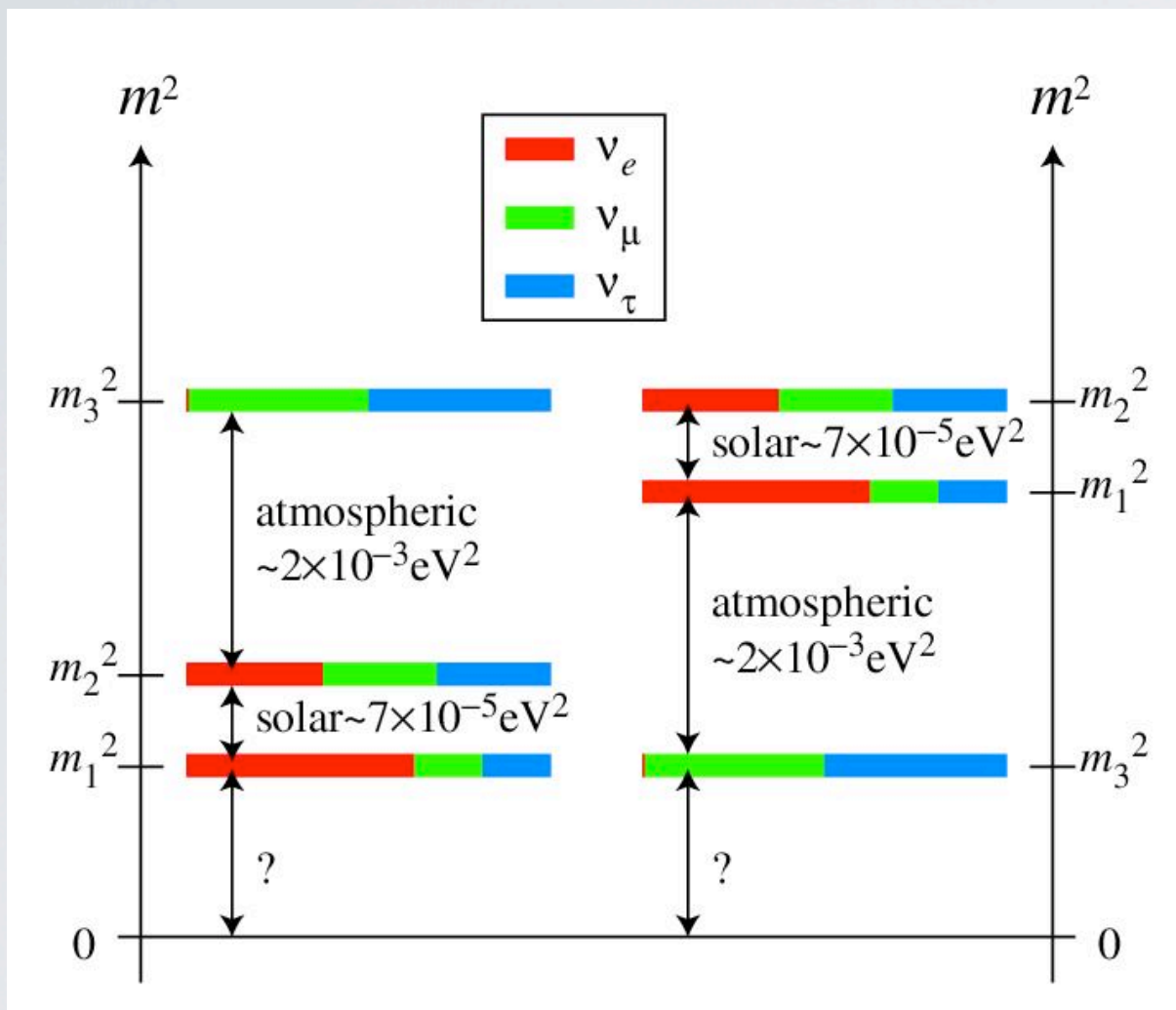
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Lecture I

LECTURE I

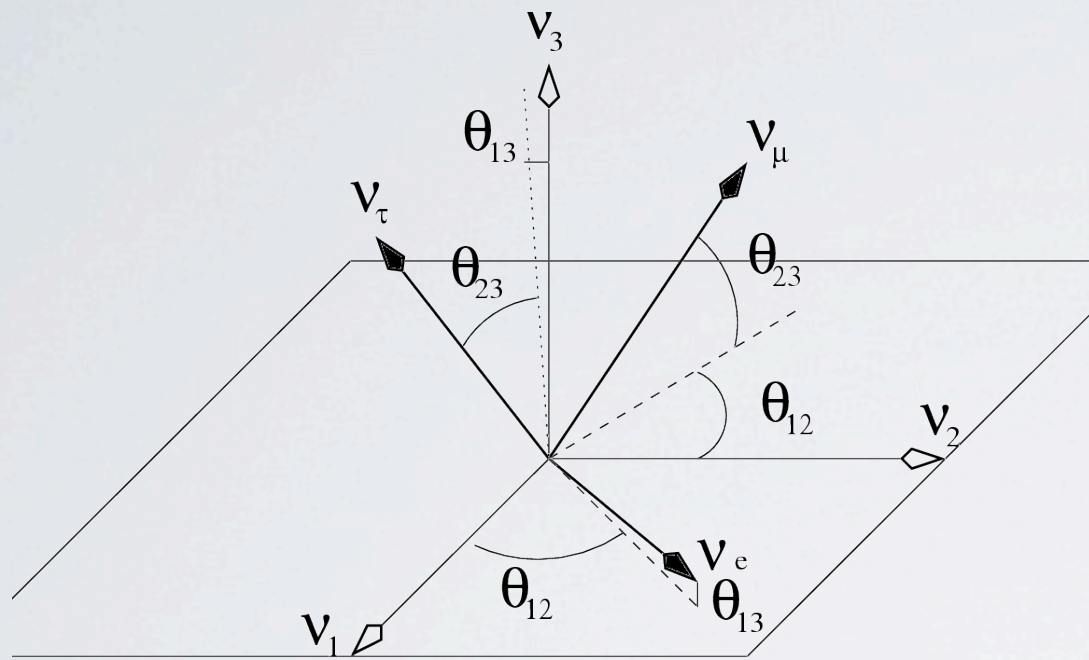
- Neutrino oscillations: you are here
- Understanding subleading transitions
- NuFact: Fluxes and rates
- CP Asymmetry revisited
- Design your experiment

NEUTRINO MASSES



- Two mass splits, one determined by solar experiments, one by atmospheric experiments.
- Absolute scale unknown
- Hierarchy (ordering) unknown.

NEUTRINO MIXING ANGLES



- Two mixing angles, measured by solar and atmospheric experiments
- θ_{12} is large but not maximal
- θ_{23} could be maximal (45°)
- θ_{13} known to be small than some 10°

Parameter	Best-fit value	3σ range
θ_{12}	33.2°	$28.7^\circ \text{ .. } 38.1^\circ$
θ_{23}	45.0°	$35.7^\circ \text{ .. } 55.6^\circ$
θ_{13}	0.0°	$0^\circ \text{ .. } 12.5^\circ$

NEUTRINO MIXING ANGLES

Atmospheric

Link

Solar

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

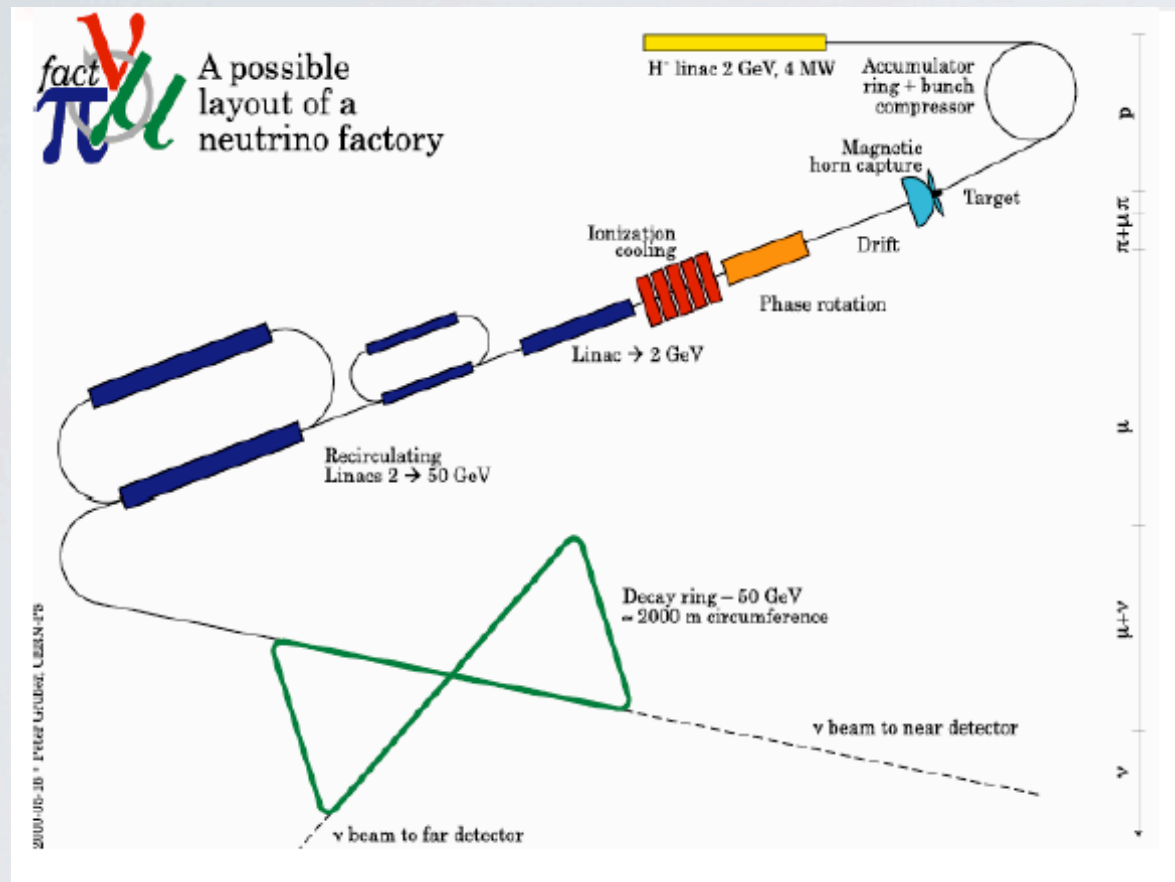
Super-Kamiokande
K2K & Minos
T2K

T2K & NOVA
Superbeams
NUFACT & β -beam

Solar experiments
SNO, KAMLAND
Super-Kamiokande

- Next generation neutrino experiments are about the link matrix and mostly about measuring CP violation.
- An interesting byproduct of some of this experiments is the possibility to measure the mass hierarchy (using matter effects, a mixed blessing).
- No access to absolute mass scale. This is the realm of neutrino DBD experiments.

FUTURE NEUTRINO FACILITIES



- The sexy physics is based on subleading transitions.
- This is because subleading transitions carry information on the link matrix.
- Understanding them is essential to understand the physics potential (and limitations) of future neutrino facilities.

SUBLEADING TRANSITIONS

Golden measurements at a neutrino factory

A. Cervera^{a,1}, A. Donini^{b,2}, M.B. Gavela^{b,3}, J.J. Gomez Cadenas^{a,4}, P. Hernández^{c,5},
O. Mena^{b,6} and S. Rigolin^{d,7}

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^d Dept. of Physics, University of Michigan, Ann Arbor, MI 48105 USA

- Exact formula (in vacuum) not very intuitive
- Expansion in small parameters: nice, manageable formula

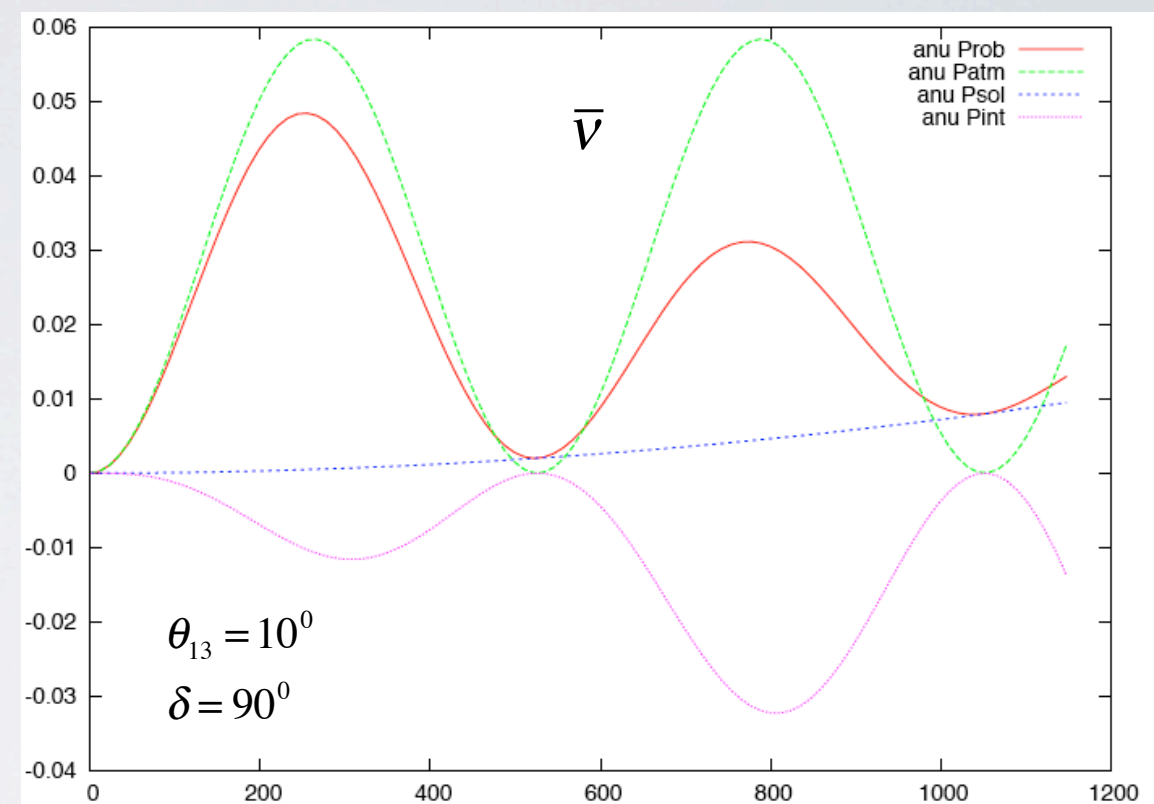
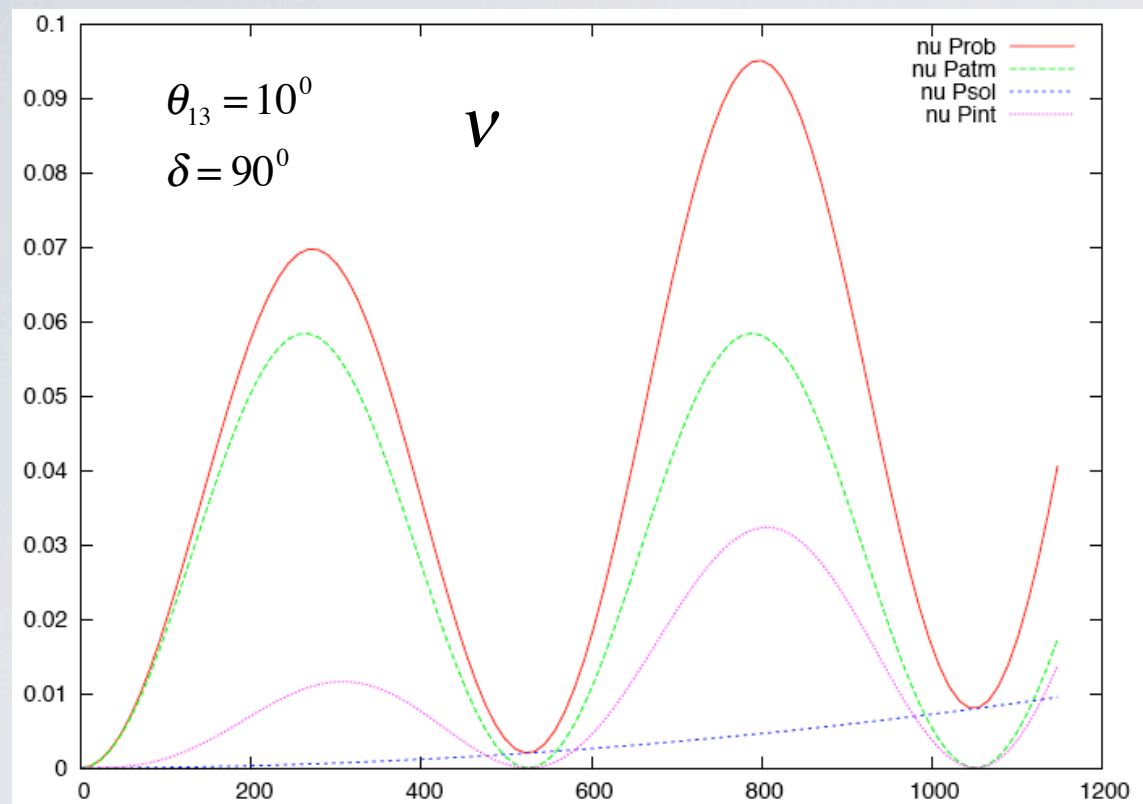
$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{k>j} \text{Re}[W_{\alpha\beta}^{jk}] \sin^2 \left(\frac{\Delta m_{jk}^2 L}{4 E} \right) \pm$$

$$\pm 2 \sum_{k>j} \text{Im}[W_{\alpha\beta}^{jk}] \sin \left(\frac{\Delta m_{jk}^2 L}{2 E} \right)$$

$$W_{\alpha\beta}^{jk} \equiv U_{\alpha j} U_{\alpha k}^* U_{\beta j}^* U_{\beta k}$$

$$\left. \begin{aligned} &\text{expand} \rightarrow \theta_{13}, \frac{\Delta_{12}}{\Delta_{13}}, \Delta_{12} L \\ &\Delta_{13} = \Delta_{23} = 2.534 \frac{\Delta m_{atm}^2}{E_\nu} \\ &\Delta_{12} = 2.534 \frac{\Delta m_{sol}^2}{E_\nu} \end{aligned} \right\} P(\nu_\mu \rightarrow \nu_e) = P_{atm} + P_{sol} + P_{int}$$

SUBLEADING TRANSITIONS



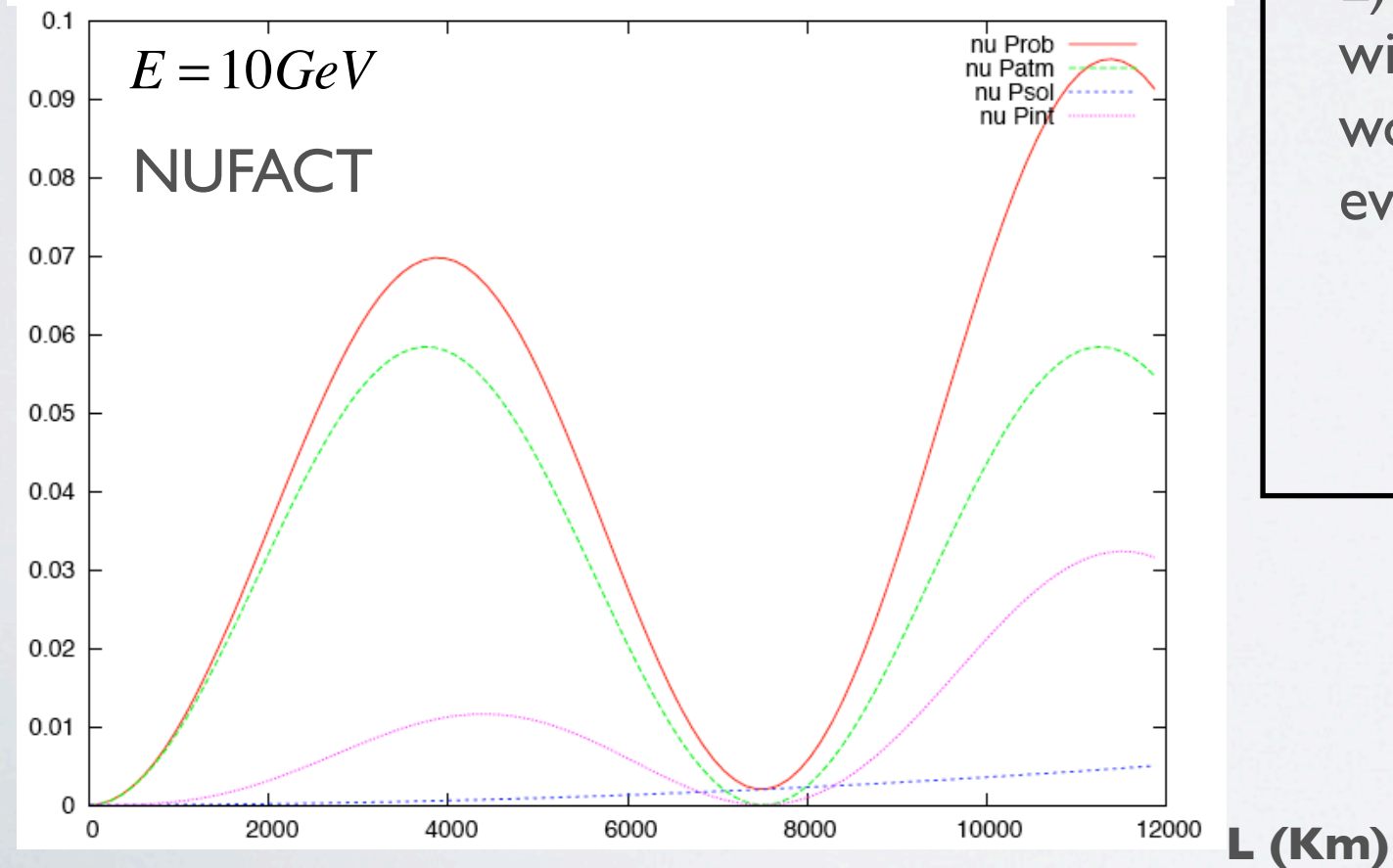
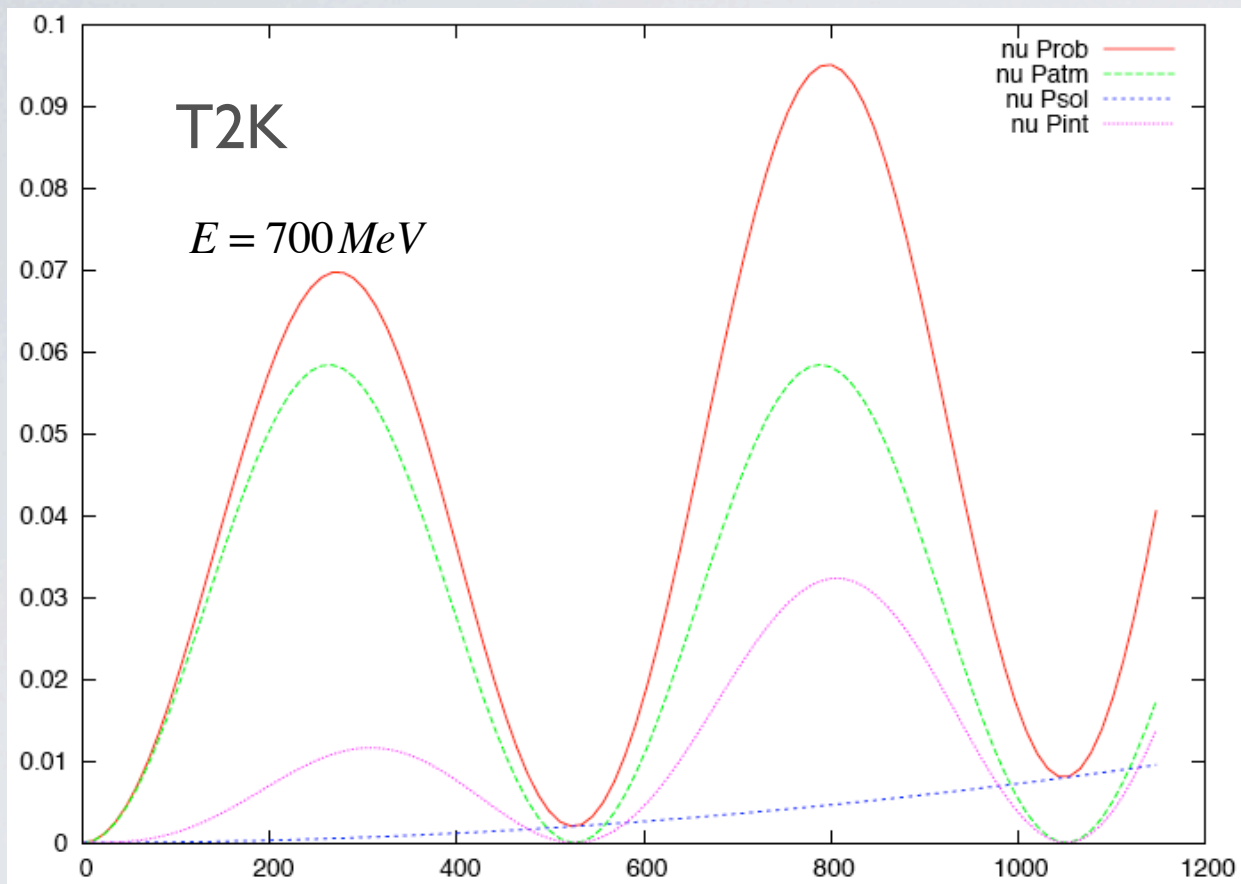
$$P(\nu_\mu \rightarrow \nu_e) = P_{atm} + P_{sol} + P_{int}$$

$$P_{atm} = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{1.267 \Delta m_{atm}^2 L}{E} \right): \text{Fast oscillation: Suppressed by } \theta_{13}$$

$$P_{sol} = \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \left(\frac{1.267 \Delta m_{sol}^2 L}{E} \right): \text{Slow oscillation: Does NOT depend of } \theta_{13}$$

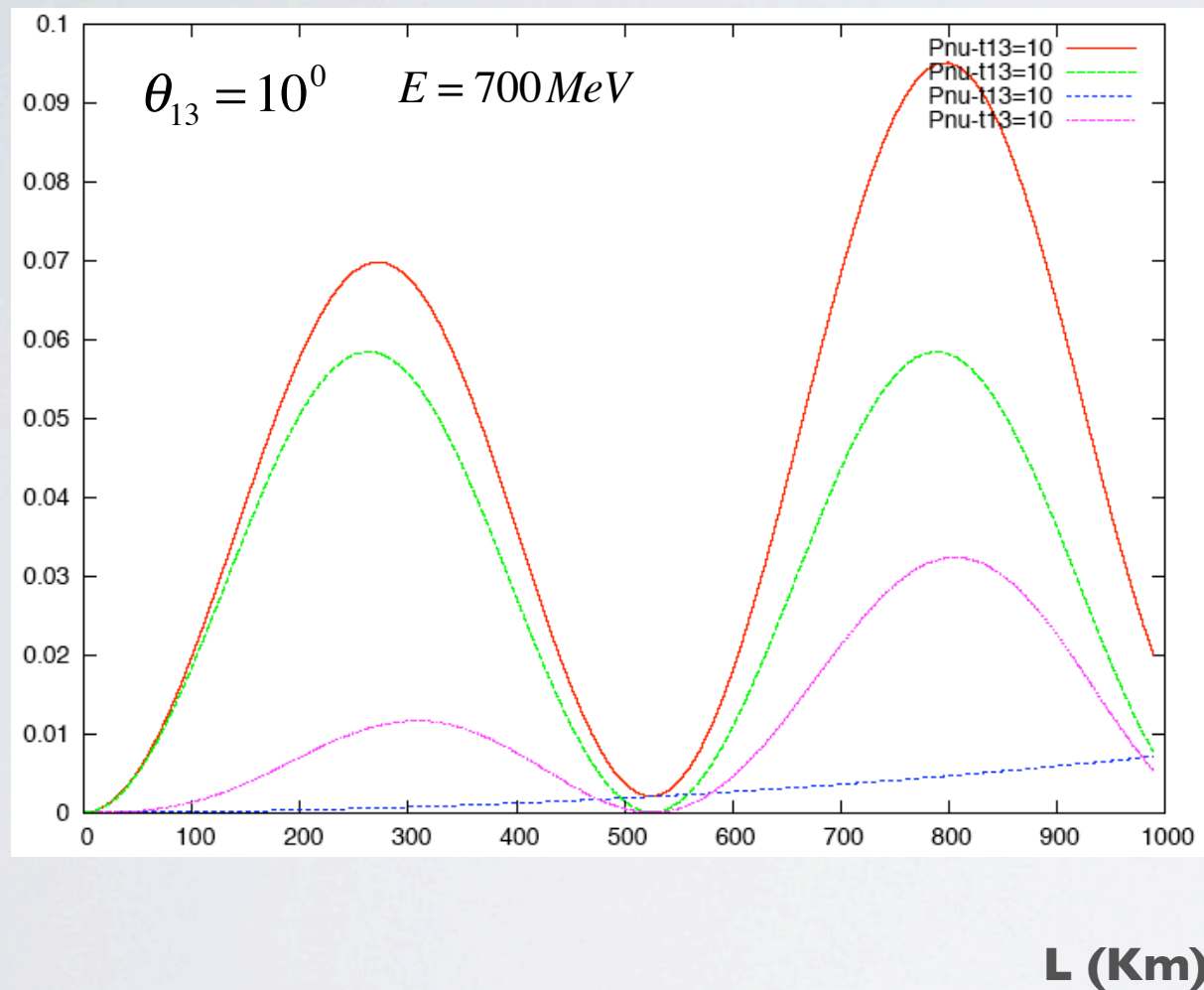
$$P_{int} = J \cos \left(\pm \delta - \frac{1.267 \Delta m_{atm}^2 L}{E} \right) \left(\frac{1.267 \Delta m_{sol}^2 L}{E} \right) \sin \left(\frac{1.267 \Delta m_{atm}^2 L}{E} \right): \text{Interference } \rightarrow \theta_{13} \text{ and } \delta$$

E/L SCALE



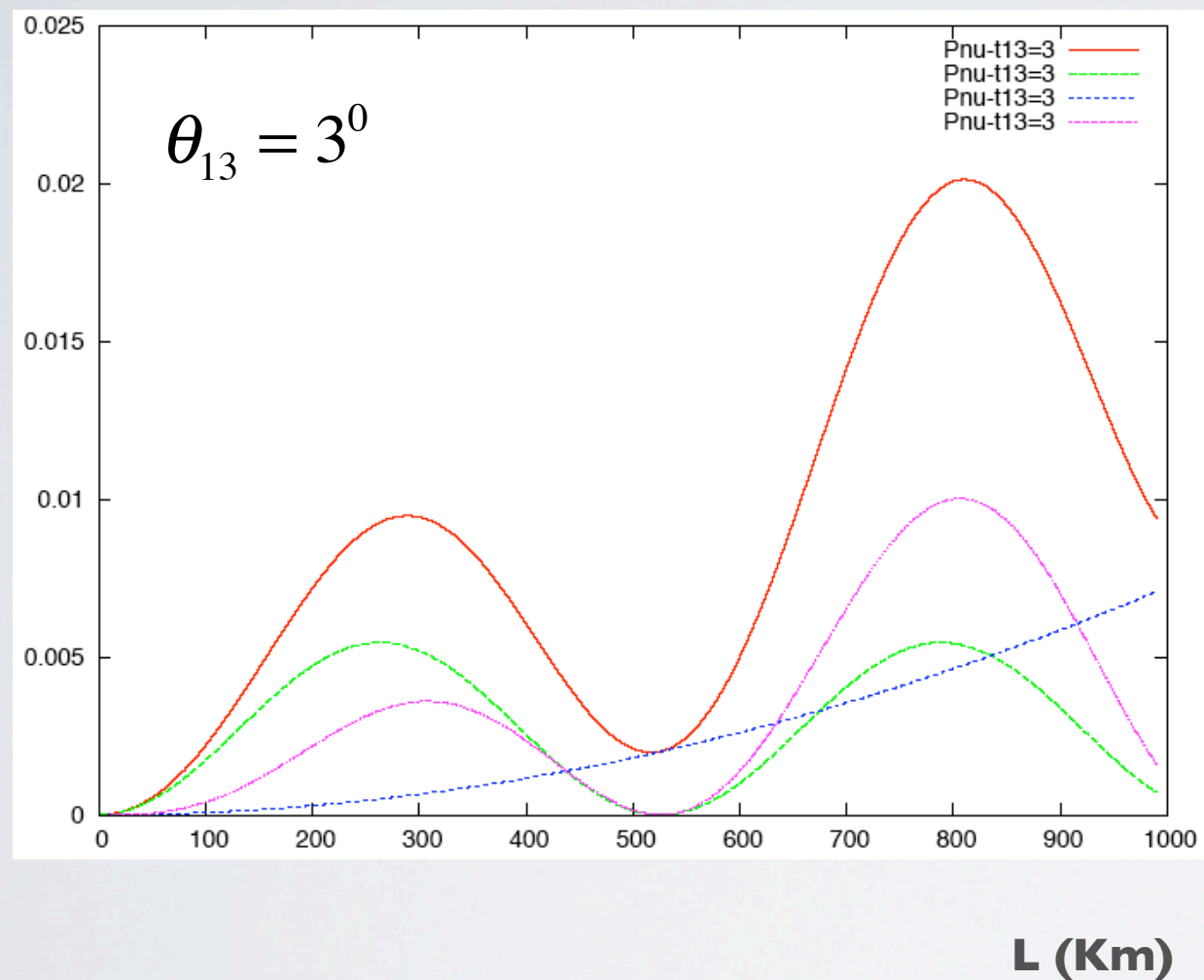
- In vacuum everything scales on E/L. For a given neutrino energy oscillation peaks at some L, given by Δm^2_{atm} .
- In principle one has freedom to choose E(or L) provided one fixes L (or E). Experiments with energies of 700 MeV and 10 GeV would have baselines of 350 or 3500 km, but everything else is invariant.

ATMOSPHERIC REGIME



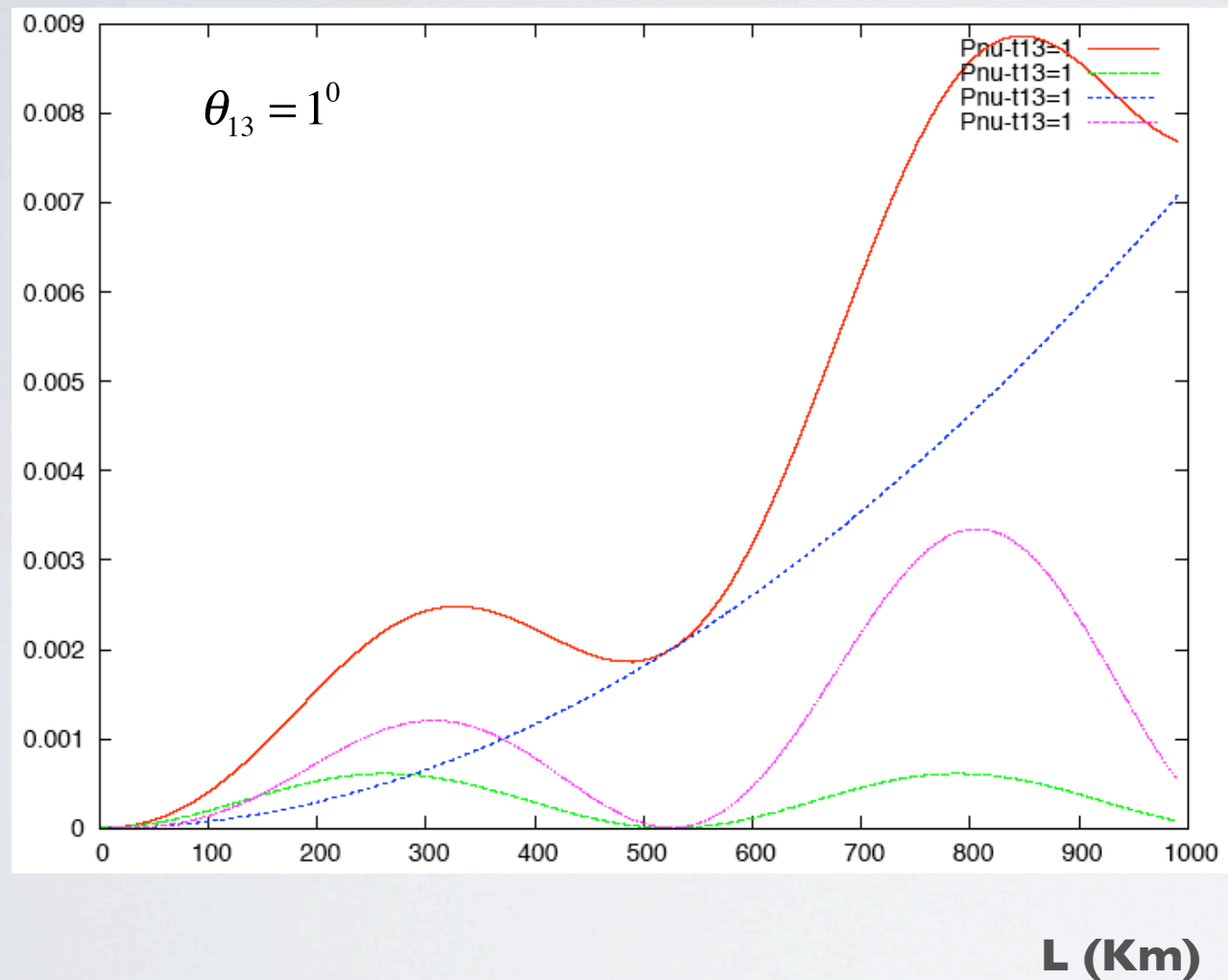
- Atmospheric oscillation is large (5%)
- Solar oscillation is small (very small at the first maximum).
- Interference is small at first maximum (1%), larger at second (3%).
- “Easy” to measure δ and θ_{13}

TRANSITION TO SOLAR REGIME



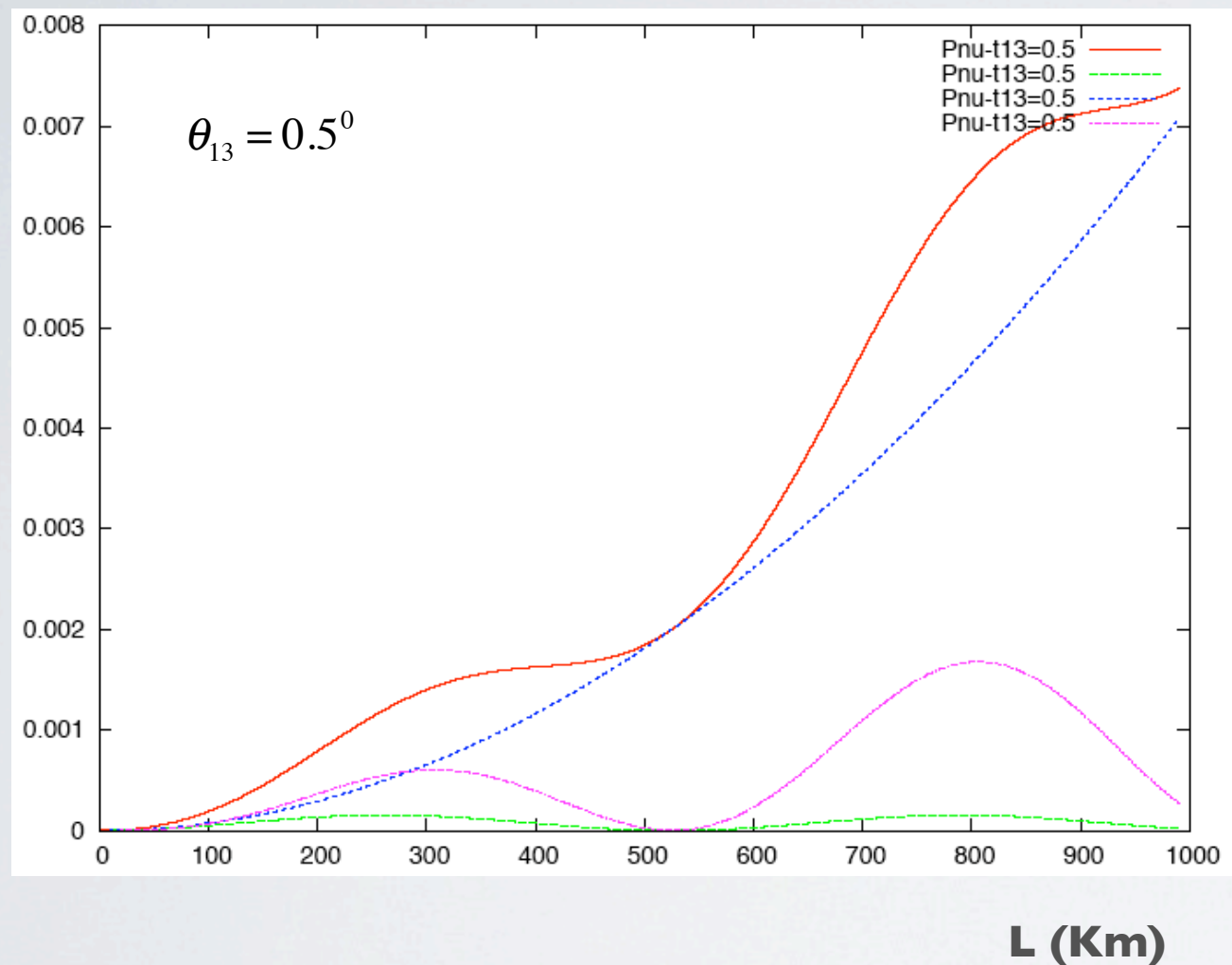
- Atmospheric oscillation decreases
- Interference is large at first maximum and larger than atmospheric term at second maximum (3%).
- One can measure δ and θ_{13} in particular if interference is measured at first and second maximum

SOLAR REGIME



- Atmospheric oscillation small, background from subleading transitions due to solar term becomes large
- The only hope to measure δ and θ_{13} is to measure interference at first and second maximum or to have a very intense beam (signal is still above background)

DEEP SOLAR REGIME



- One is hitting physics limit. The background from solar subleading transitions is of the same order than the atmospheric signal
- Interference is becoming small, as atmospheric transition also vanishes.

RECIPES TO MEASURE θ_{13}

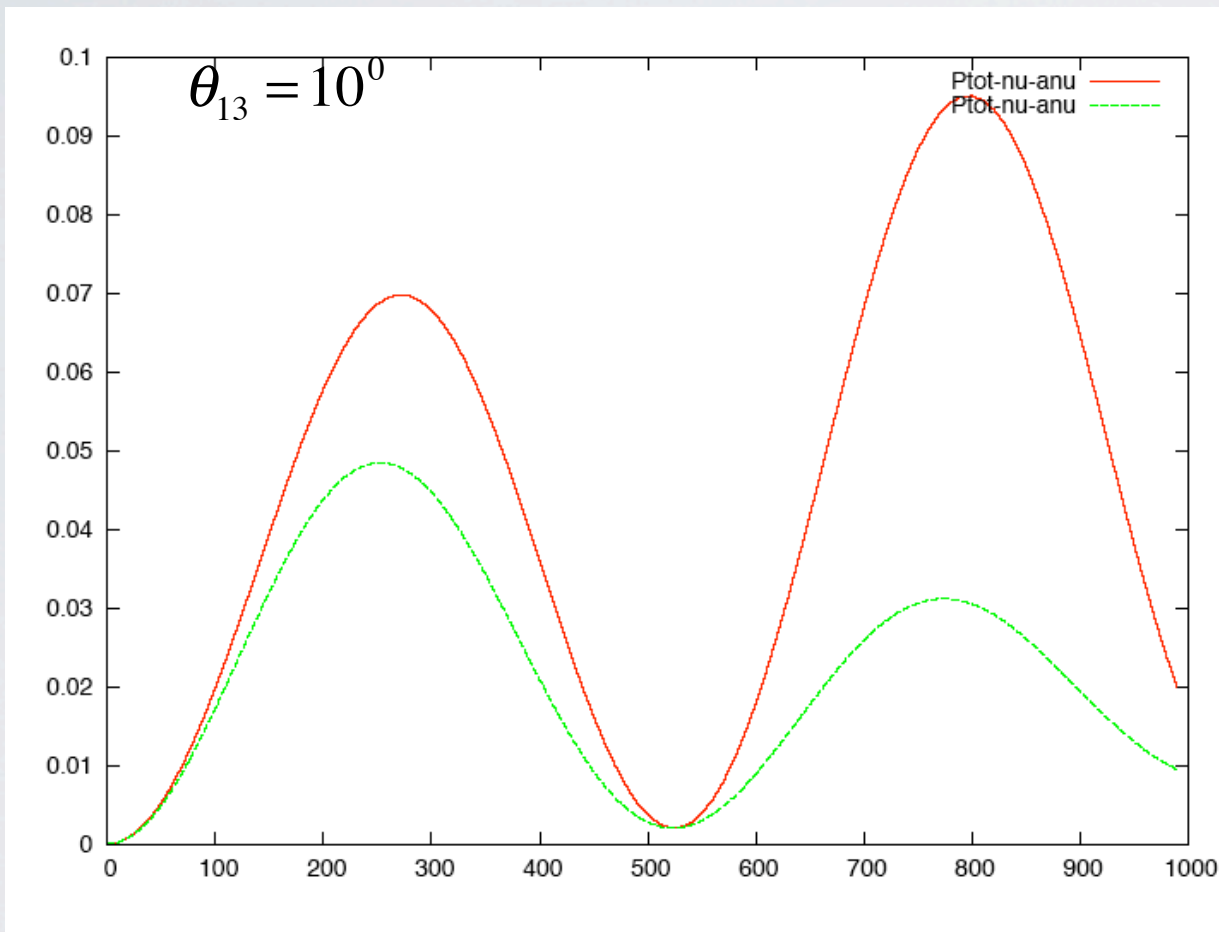
- Transition probabilities are small. Need very intense beams
- For θ_{13} “large” ($\sim 10^\circ$) atmospheric term dominates solar term. Go to (first) maximum
- For θ_{13} small ($< 1^\circ$) solar term dominates atmospheric term. Go off peak.
- Choose E and set L or vice-versa (keep E/L at atmospheric first maximum)

HOMEWORK

- The dominant oscillation has been established with a “weak” beam (K2K). Why do we need intense beams to explore the subdominant oscillation?
- Suppose T2K finds marginal evidence that θ_{13} is “large”. How would you choose E/L for the next generation experiment?
- What if T2K does not find a signal, indicating that θ_{13} is small?
- Oscillation probability is larger in second maximum. Does that mean that one should choose second maximum region rather than first for performing experiments? Why?
- HW: Pros and cons of going to second peak, how close to source in solar regime, assuming perfect detector and beam what limits the measurement of θ_{13} (estimate numerically)

CP VIOLATION

$$P_{\text{int}} = J \cos\left(\pm\delta - \frac{1.267\Delta m_{\text{atm}}^2 L}{E}\right) \left(\frac{1.267\Delta m_{\text{sol}}^2 L}{E}\right) \sin\left(\frac{1.267\Delta m_{\text{atm}}^2 L}{E}\right)$$



$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \text{ if } \delta \neq 0, \pi, 2\pi, \dots$$

- CP violation arises due (exclusively) to the interference term that results in a different transition probability for neutrinos and antineutrinos

CP ASYMMETRY

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

$$\omega_{atm} = \frac{1.267 \Delta m_{atm}^2 L}{E}$$

$$\omega_{sun} = \frac{1.267 \Delta m_{sol}^2 L}{E}$$

$$P_{atm} = \sin^2 \theta_{23} \sin^2 \omega_{atm} \sin^2 2\theta_{13} \approx X \cdot \theta_{13}^2, \quad X = 4 \sin^2 \theta_{23} \sin^2 \omega_{atm}$$

$$P_{sun} = \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \left(\frac{1.267 \Delta m_{sol}^2 L}{E} \right) = \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \omega_{sun} = Y$$

$$\begin{aligned} P_{int} &= J \cos \left(\pm \delta - \frac{1.267 \Delta m_{atm}^2 L}{E} \right) \left(\frac{1.267 \Delta m_{sol}^2 L}{E} \right) \sin \left(\frac{1.267 \Delta m_{atm}^2 L}{E} \right) = \\ &= \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \omega_{sun} \sin \omega_{atm} \cos(\pm \delta - \omega_{atm}) = Z \cos(\pm \delta - \omega_{atm}), \\ Z &= \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \omega_{sun} \sin \omega_{atm} \approx \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \omega_{sun} \sin \omega_{atm} \end{aligned}$$

$$P_{int}^{\nu} = Z \cos \theta_{13} \cos(\delta - \omega_{atm}) = Z (\cos \delta \cos \omega_{atm} + \sin \delta \sin \omega_{atm})$$

$$P_{int}^{\bar{\nu}} = Z \cos \theta_{13} \cos(\delta + \omega_{atm}) = Z (\cos \delta \cos \omega_{atm} - \sin \delta \sin \omega_{atm})$$

$$P_{\nu} = P_{atm} + P_{sun} + P_{int}^{\nu} \approx X \cdot \theta_{13}^2 + Y + Z (\cos \delta \cos \omega_{atm} + \sin \delta \sin \omega_{atm})$$

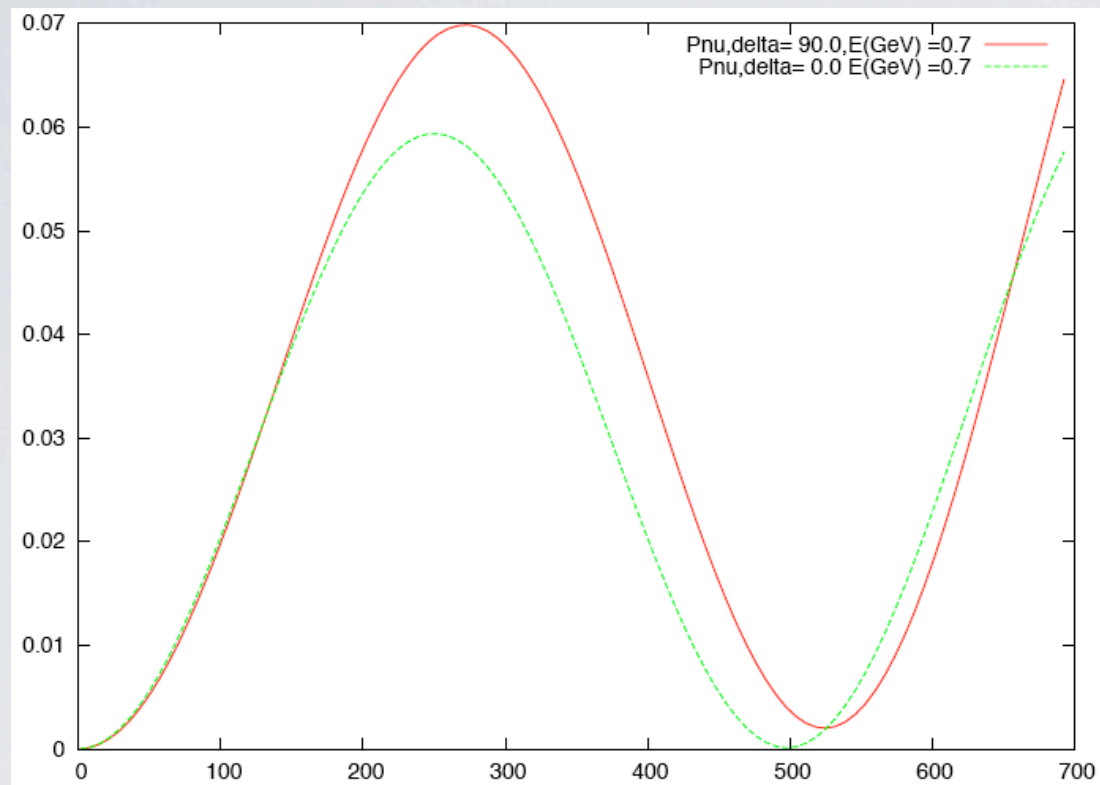
$$P_{\bar{\nu}} = P_{atm} + P_{sun} + P_{int}^{\bar{\nu}} \approx X \cdot \theta_{13}^2 + Y + Z (\cos \delta \cos \omega_{atm} - \sin \delta \sin \omega_{atm})$$

$$P_{\nu} - P_{\bar{\nu}} = 2Z \sin \delta \sin \omega_{atm}$$

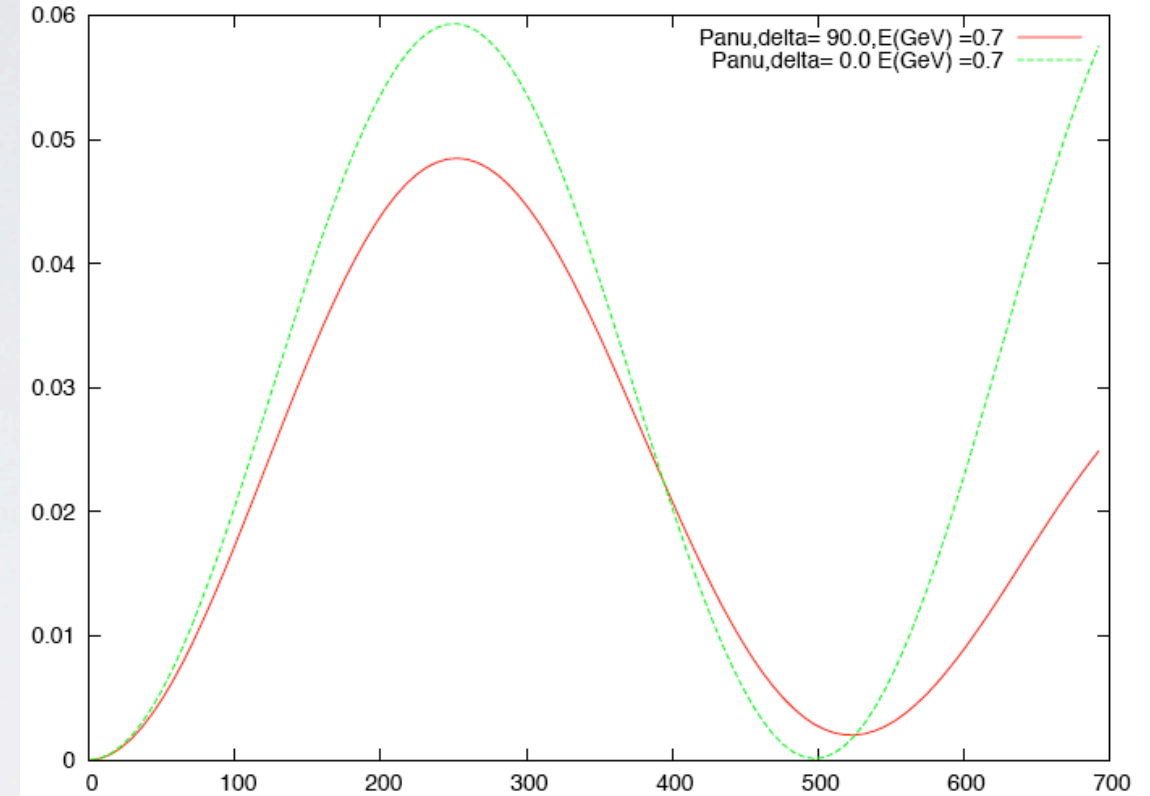
$$P_{\nu} + P_{\bar{\nu}} = 2P_{atm} + 2P_{sun} + 2Z \cos \delta \cos \omega_{atm} = 2(X \cdot \theta_{13}^2 + Y + Z \cos \delta \cos \omega_{atm})$$

CP ASYMMETRY

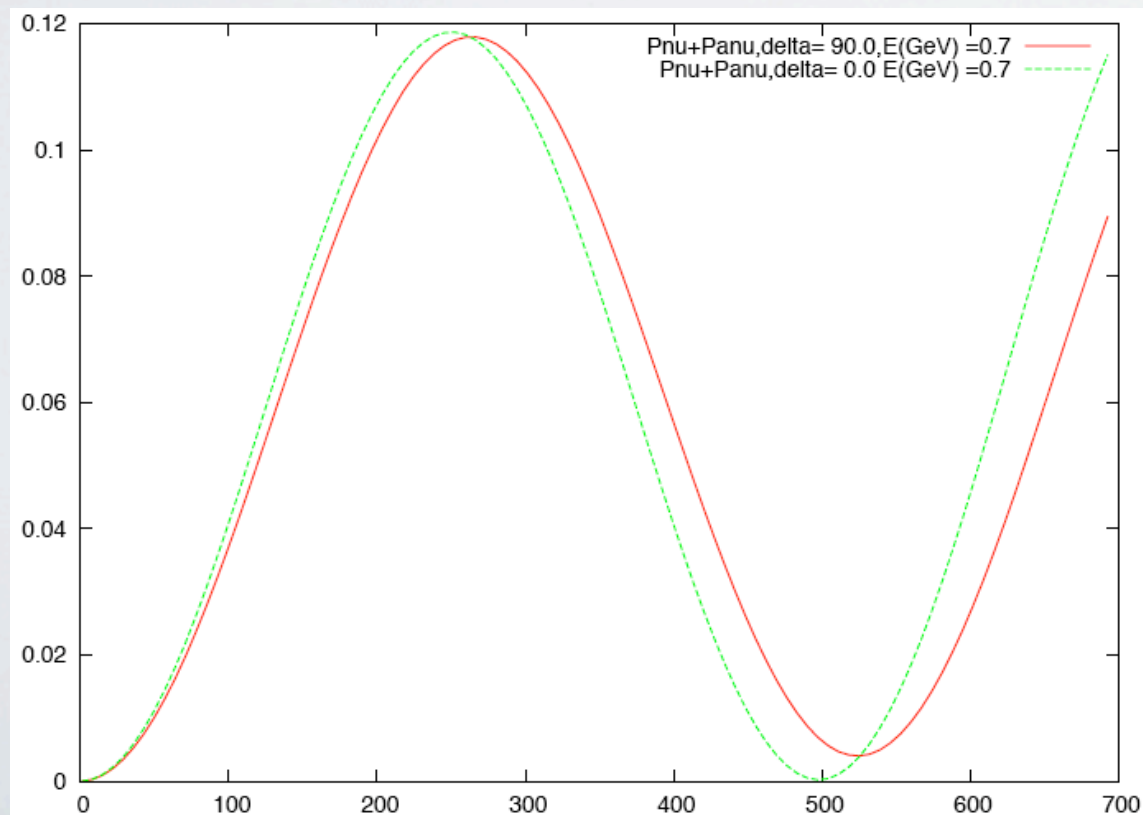
$$P_\nu = P_{atm} + P_{sun} + P_{int}^\nu \approx X \cdot \theta_{13}^2 + Y + Z(\cos \delta \cos \omega_{atm} + \sin \delta \sin \omega_{atm})$$



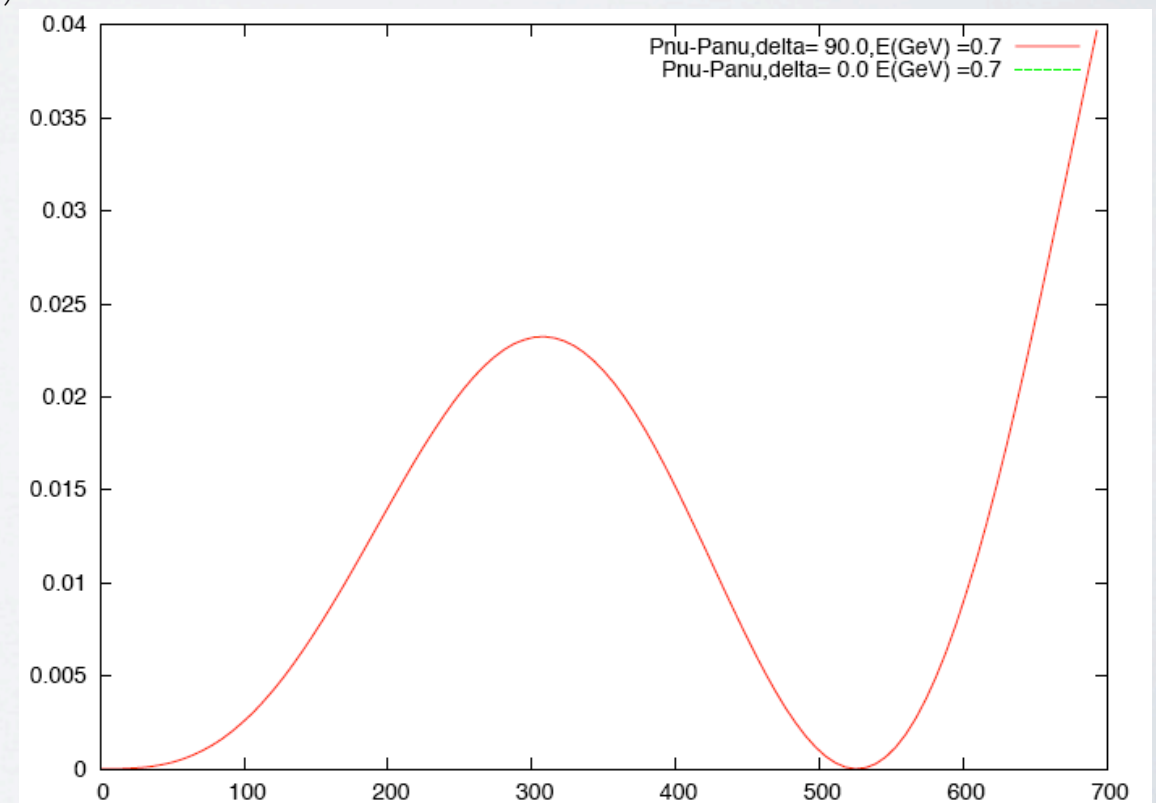
$$P_{\bar{\nu}} = P_{atm} + P_{sun} + P_{int}^{\bar{\nu}} \approx X \cdot \theta_{13}^2 + Y + Z(\cos \delta \cos \omega_{atm} - \sin \delta \sin \omega_{atm})$$



$$P_\nu + P_{\bar{\nu}} = 2P_{atm} + 2P_{sun} + 2Z \cos \delta \cos \omega_{atm} = 2(X \cdot \theta_{13}^2 + Y + Z \cos \delta \cos \omega_{atm})$$



$$P_\nu - P_{\bar{\nu}} = 2Z \sin \delta \sin \omega_{atm}$$

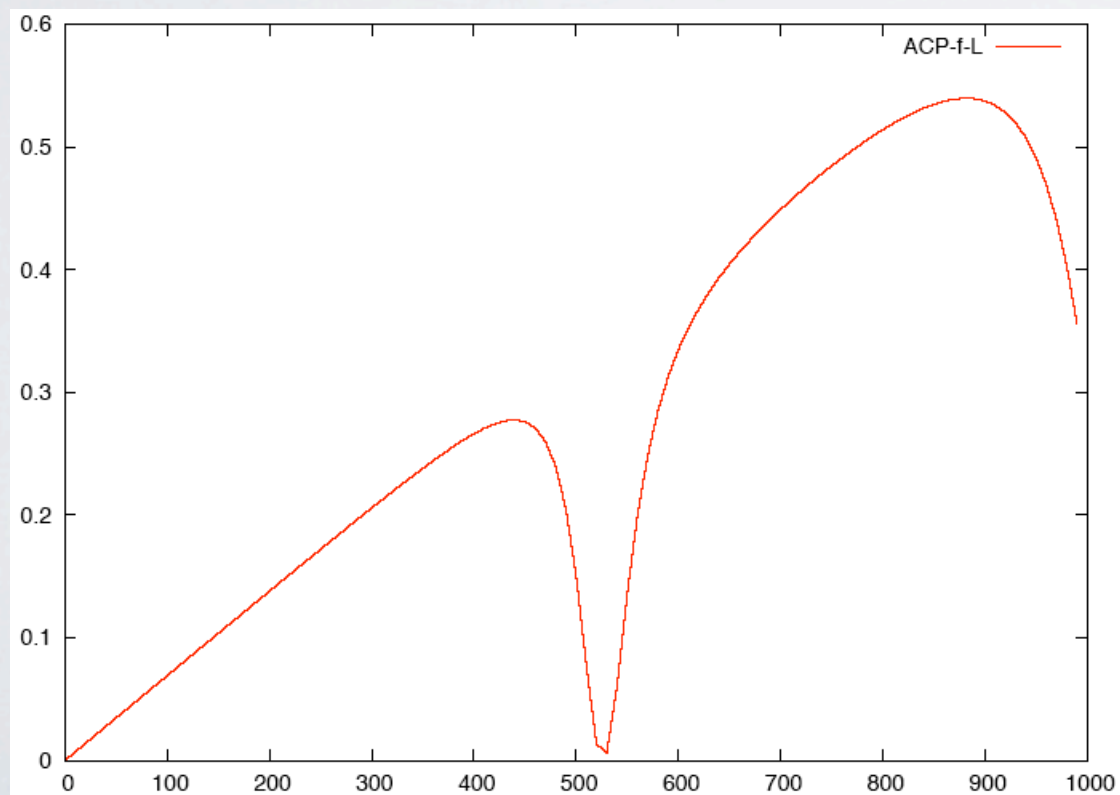
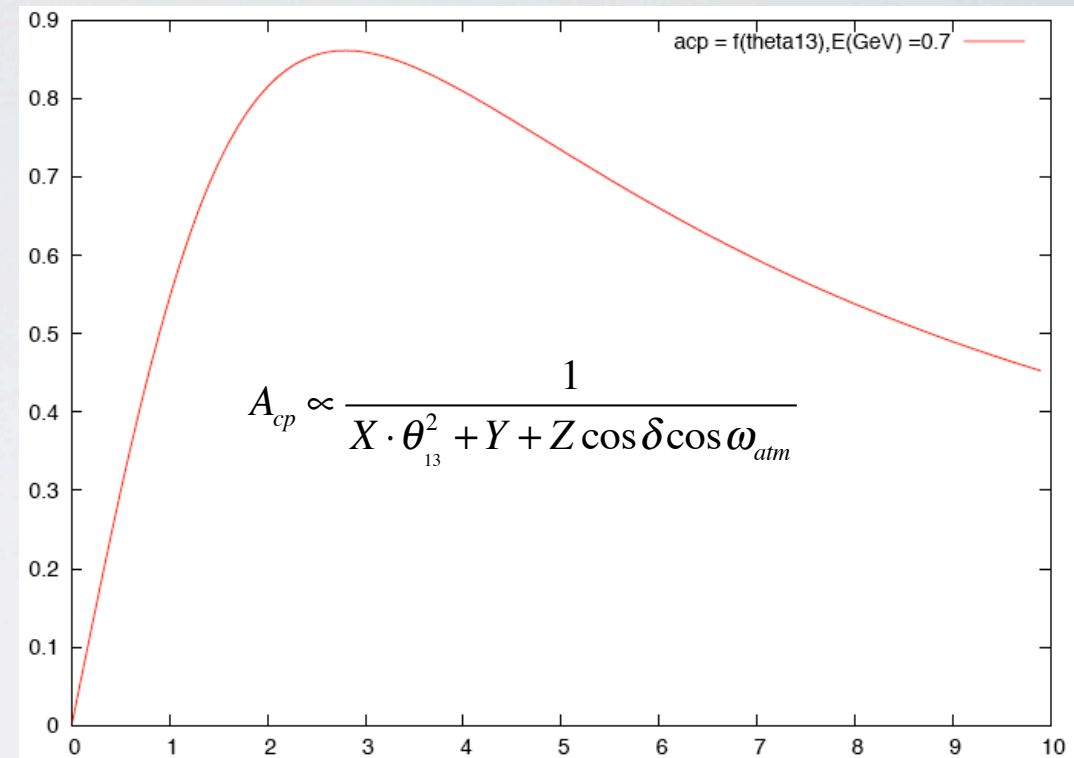
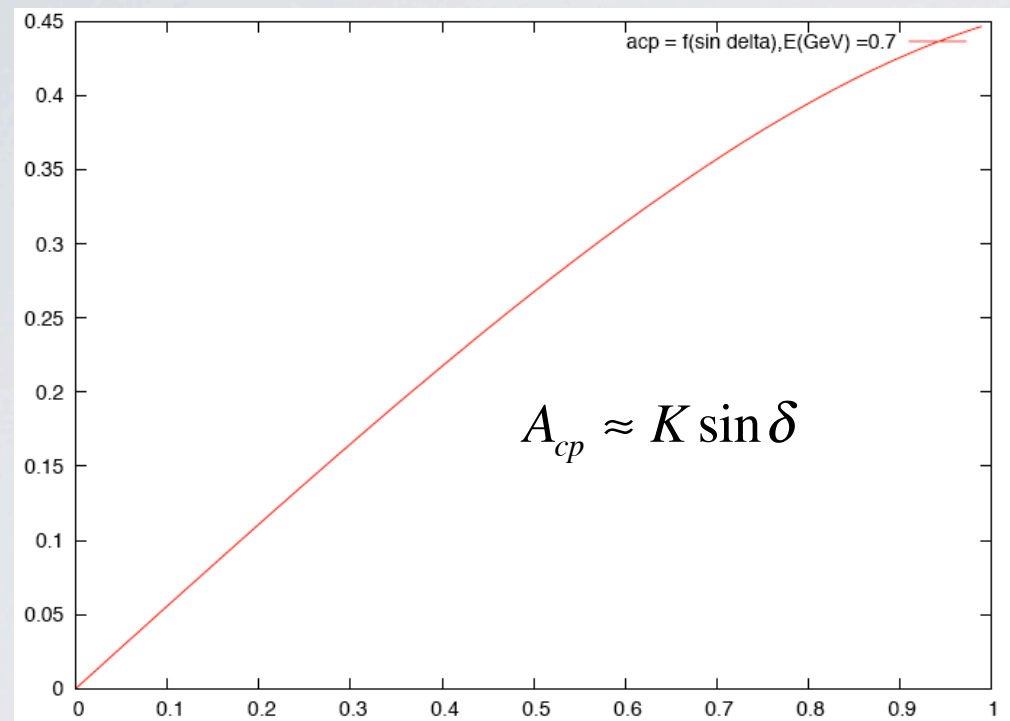


CP ASYMMETRY

$$A_{cp} = \frac{P_\nu - P_{\bar{\nu}}}{P_\nu + P} = \frac{Z \sin \omega_{atm}}{X \cdot \theta_{13}^2 + Y + Z \cos \delta \cos \omega_{atm}} \sin \delta$$

- To isolate the interference term one can subtract transitions probabilities. To normalize the difference between transition probabilities to the magnitude of the effect one divides by the sum. Thus one is lead to define a CP asymmetry as an estimator of the magnitude of CP violation

CP ASYMMETRY

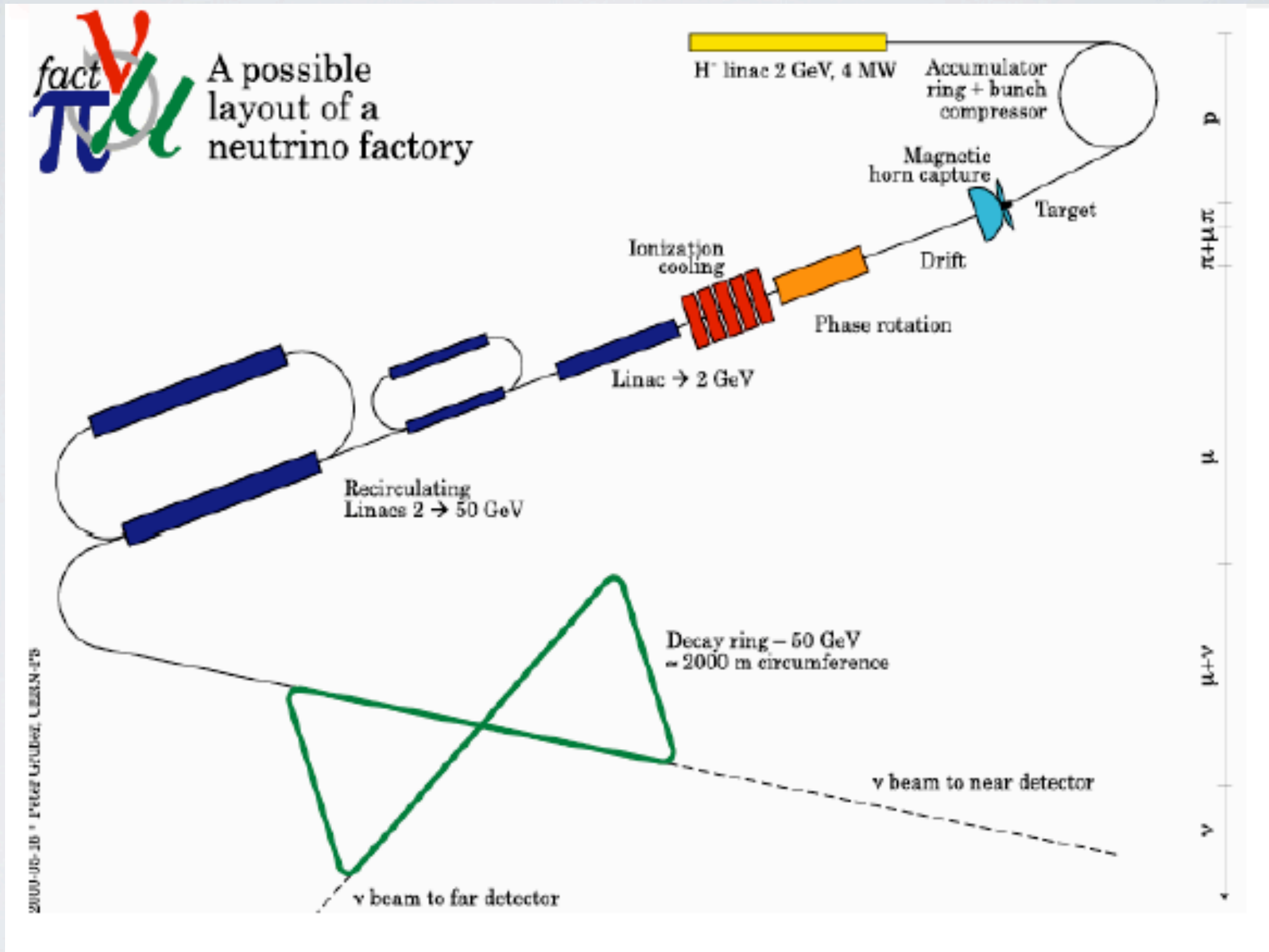


- ACP is a linear function of δ
- ACP peaks for small values of θ_{13} !
- ACP larger at the second maximum!

HOMEWORK

- Why ACP is a good estimator of CP?
- For $\delta=90^\circ$ ACP is larger for $\theta_{13}=3^\circ$ than for $\theta_{13}=10^\circ$ Is then true that sensitivity to δ will be better at $\theta_{13}=3^\circ$ than at $\theta_{13}=10^\circ$
- Why ACP does not peak at oscillation maximum? Do you expect to have max sensitivity to δ at the peak of ACP?
- Discuss pros and cons of going to second node to measure δ
- Assume you can run an experiment with no systematics and infinite statistical precision. What would limit the sensitivity to δ ?

THE NEUTRINO FACTORY

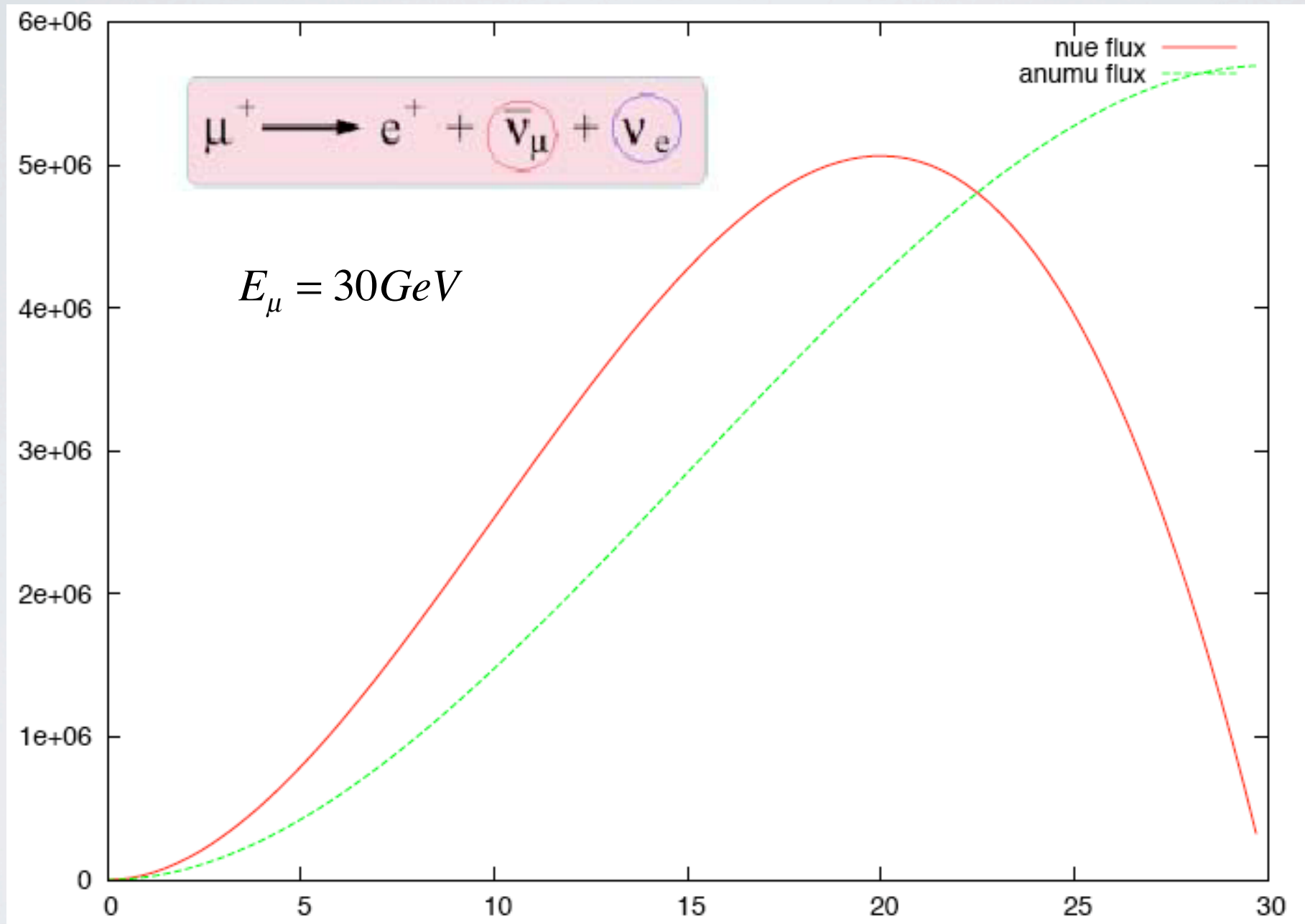


FLUXES

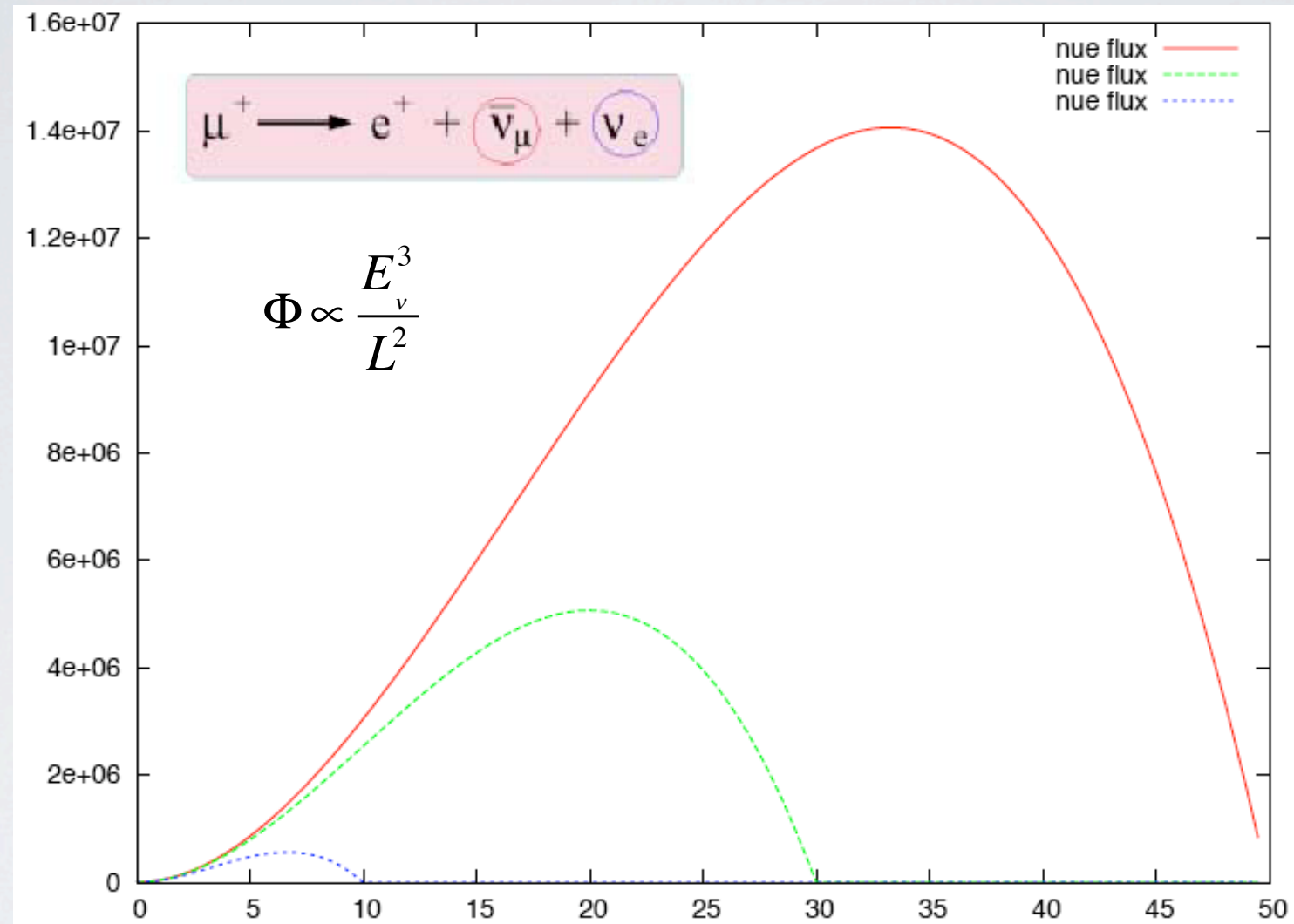
$$\begin{aligned}\Phi_{\nu_\mu, \bar{\nu}_\mu} &= \frac{1}{L^2} \frac{d^2 N_{\nu_\mu, \bar{\nu}_\mu}}{dy d\Omega} = \frac{4n_\mu}{L^2 \pi m_\mu^6} E_\mu^4 y^2 (1 - \beta \cos \varphi) \\ &\quad \times \left\{ [3m_\mu^2 - 4E_\mu^2 y (1 - \beta \cos \varphi)] \right. \\ &\quad \left. \mp \mathcal{P}_\mu [m_\mu^2 - 4E_\mu^2 y (1 - \beta \cos \varphi)] \right\}, \\ \Phi_{\nu_e, \bar{\nu}_e} &= \frac{1}{L^2} \frac{d^2 N_{\nu_e, \bar{\nu}_e}}{dy d\Omega} = \frac{24n_\mu}{L^2 \pi m_\mu^6} E_\mu^4 y^2 (1 - \beta \cos \varphi) \\ &\quad \times \left\{ [m_\mu^2 - 2E_\mu^2 y (1 - \beta \cos \varphi)] \right. \\ &\quad \left. \mp \mathcal{P}_\mu [m_\mu^2 - 2E_\mu^2 y (1 - \beta \cos \varphi)] \right\}.\end{aligned}$$

Here, $\beta = \sqrt{1 - m_\mu^2/E_\mu^2}$, E_μ is the parent muon energy, $y = E_\nu/E_\mu$, n_μ is the number of useful muons per year obtained from the storage ring, and L is the distance to the detector. φ is the angle between the beam axis and the direction

BEAMS



FLUXES & BEAM ENERGY



- Fluxes (thus rates) increases dramatically with muon Energy

RIGHT & WRONG SIGN MUONS

$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$\bar{\nu}_\mu + N \longrightarrow \mu^+ + X$$

right sign muon

CC

$$\bar{\nu}_\mu + N \longrightarrow \bar{\nu}_\mu + X$$

NC

$$\nu_e \overset{\text{osc}}{\sim} \nu_\mu$$

$$\nu_\mu + N \longrightarrow \mu^- + X$$

wrong sign muon

SIGNAL

RIGHT & WRONG SIGN MUONS

$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$\bar{\nu}_\mu + N \longrightarrow \mu^+ + X$$

right sign muon

CC

$$\bar{\nu}_\mu + N \longrightarrow \bar{\nu}_\mu + X$$

NC

$$\nu_e \overset{\text{osc}}{\sim} \nu_\mu$$

$$\nu_\mu + N \longrightarrow \mu^- + X$$

wrong sign muon

SIGNAL

HOMEWORK

- Compute the error on ACP (tip: relate the number of right and wrong sign muons to oscillation probabilities), express ACP in terms of right and wrong sign muons and take derivatives to obtain δACP
- Compute ACP over its error (this is the relevant quantity for CP measurements... why?)
- Do you see a significant difference between ACP and $\delta\text{ACP}/\text{ACP}$?
- Does your observation dictates a new strategy? How do you measure CP?
- Any different strategy between “Gedankenexperiment T2K” and GE NuFact?

HOMEWORK

- Based on the material covered today, design your NuFact experiment:
- You have infinite funding and the NuFact machine works at any desired energy!
- Which muon energy would you choose? Any limitations? (remember, not in the machine)
- Then at which baseline(s) would you place your detector(s)?
- What feature is essential for your detector?
- Discuss your strategies to measure θ_{13} and δ in the hypothesis of solar and atmospheric regime