Monoenergetic Neutrino Beam for Long Baseline Experiments

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1.Introduction

Neutrino Observation Indicate Neutrino Masses and Lepton Mixings

Solar Neutrino / Reactor (Kamland)

Atmospheric Neutrino / K2K /MINOS

$\delta m^2_{21}, \theta_{12}$

$\delta m^2_{31}, \theta_{23}$

Two Mixing Angles and Two Mass Square differences

θ_{13} Small ; upper bound from Reactor (Chooz)

δ CP Phase ; Unknown (no constraint)

In future Experiments

Precision Measurement for $\theta_{ij}, \delta m^2_{ij}$

Particular interest Determination of θ_{13}, δ

Needs for well-controlled neutrino beam(s)

Current Ideas

$$Superbeam、NeutrinoFactory、BetaBeam$$

Superbeam

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$e^+ + \nu_e\ (\sim 0.1\%)$: $\nu_\mu \rightarrow \nu_e$ Fake events

Basically same as K2K

T2K, MINOS, NOνA

$Neutrino Factory$

S.Geer

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

$\nu_e \rightarrow \nu_\mu$ Will be used

Charge ID $\nu_\mu - > \mu^-$ VS $\bar{\nu}_\mu - > \mu^+$

Wrong Sign Muon

High energy neutrinos $->$ Deep inelastic scattering

$->$ energy is reconstructed statistically

If charge ID is perfect, NO “Fake Event”

Beta Beam

Zucchelli

Neutrinos from beta decays

$$^{18}\mathrm{Ne} \rightarrow {}^{18}\mathrm{F} + e^{+} + \nu_e$$

$$^{6}\mathrm{He} \rightarrow {}^{6}\mathrm{Li} + e^{-} + \bar{\nu}_e$$

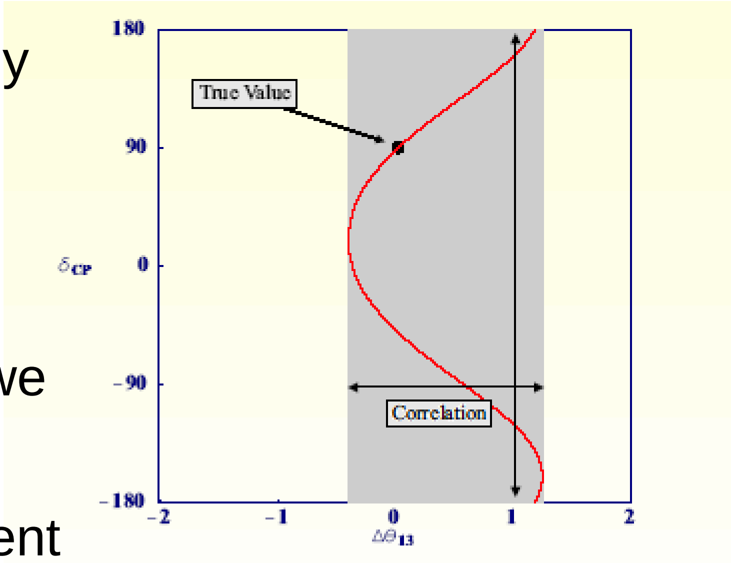
Low energy : : Quasi Elastic events

$->$ clean

Technically most difficult

Measurement of Oscillation Parameters

Fixing values of parameters and neutrino energy
→Oscillation Probability



Rigolin nufact05

By measuring the probability with one energy, we draw a supersurface of the parameter space.

With different oscillation mode, we obtain different surface

By overlapping supersurfaces for different energies and/or oscillation modes, we obtain “correct” values for parameters, **in principle**

In a real situation, dificulties due to

○Supersurface is not a “surface” but a volume,with a width due to uncertainties.
○Similar shape for supersurface for similar energy

→ How to get “thin” surface

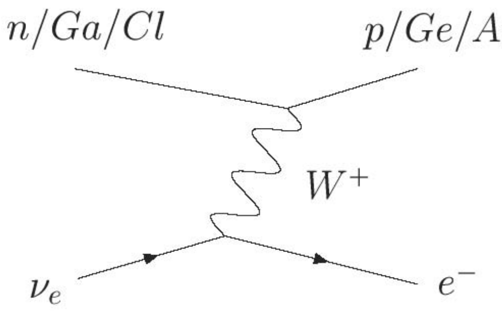
Note on Measurement :

We measure only charged leptons created by neutrinos

→ induces energy uncertainty

☆Low energy neutrino :: quasi elastic scattering

SuperBeam BetaBeam



Elastic scattering

Reconstruction of neutrino energy by the neutrino and the charged lepton

However, there are uncertainties in measurement on the direction and the energy of charged leptons

Furthermore, intrinsic uncertainty due to Fermi motion/energy

☆High energy neutrino :: inelastic scattering

(SuperBeam) Neutrino Factory

No “direct” measurement on neutrino energy

Statistically “reconstruct” the distribution of neutrino energy

→ **More uncertainty on “neutrino energy**

New Idea to determine Neutrino Energy at a Detector ?

2.Basic Idea for capture beam

Electron Capture

$$(Z, A) + e^- \to (Z-1, A) + \nu_e$$

$$M(Z, A) + \Delta E = M(Z-1) + Q$$

M : Atom mass ΔE : Binding energy $(Q \ll M)$

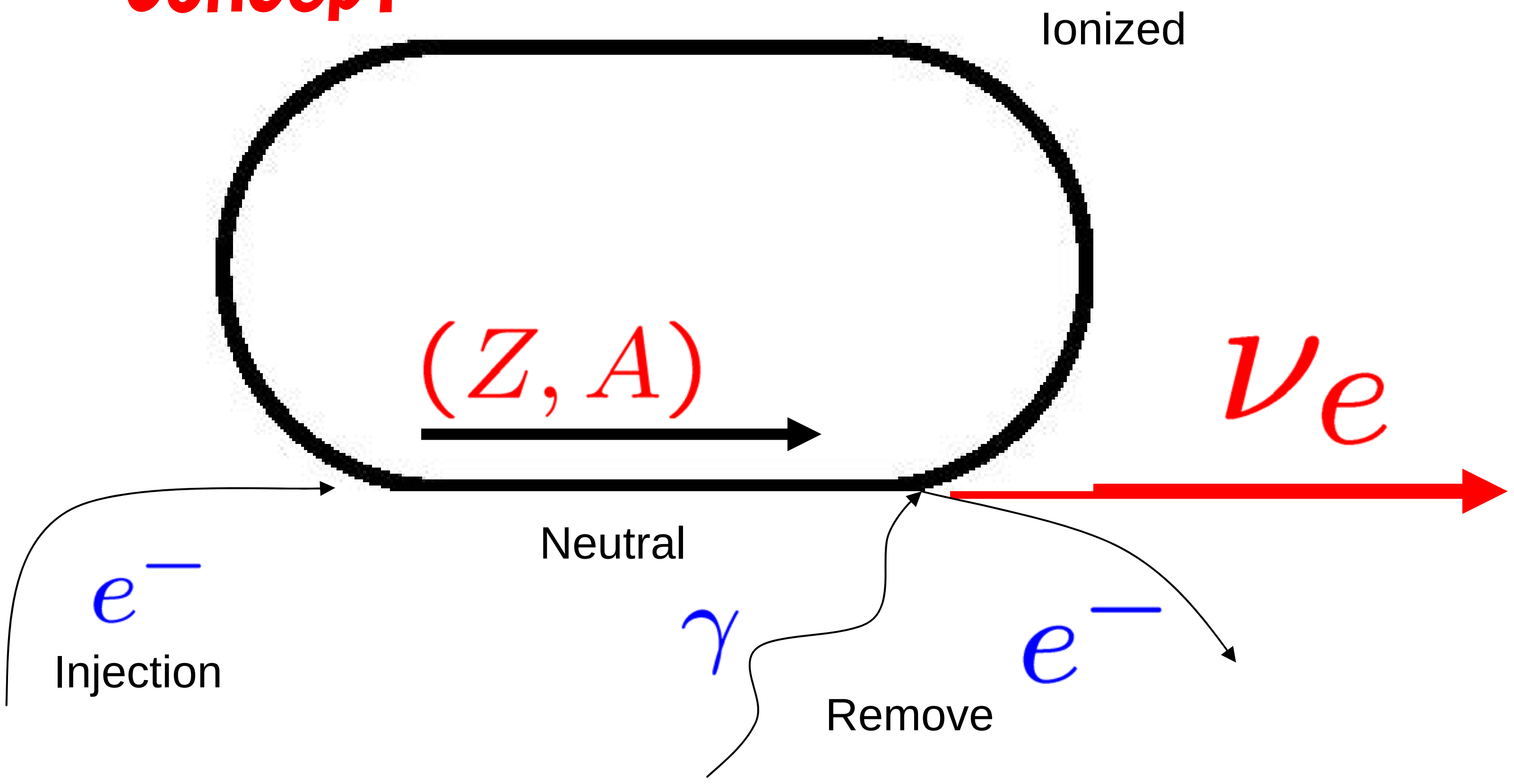
Q Neutrino Energy at Rest : Definite

$BoostingMotherNuclei\,(Z, A)$ by γ_m

Control Neutrino Energy and Get Monoenergetic Neutrino Beam

Experimental Setup

Concept



Condition on Q (and γ_m)

Neutrino Energy in Lab $0 < E_\nu < 2\gamma_m Q$

Highest Energy

(Which Energy Range ?)

Assuming a beam pointing to a detector:

At first glance

$$\left.\frac{\delta m^2 L}{4E_\nu}\right|_{E_\nu = 2\gamma_m Q} = P \quad (\text{ say, } = \tfrac{\pi}{2})$$

determines $$\gamma_m = \frac{\delta m^2 L}{8P}\frac{1}{Q}$$

Neutrinos “fly” $L' \equiv L/\gamma m$ Baseline in rest frame

Inverse of “Quality Factor” (Zucchelli)

Larger γm Preferable

to get higher intensity beam

⇓

Lower Q better

However, Lower Q → Longer lifetime τ
for mother nucleus

Constraint from “our (experiment)” lifetime T

T : At most several years

$$\tau\gamma_m < T \quad \Rightarrow \quad \frac{\delta m^2 L}{8PT} < Q/\tau$$

Upper bound for γ_m **“Lower bound” for Q**

Find a nuclei with lower Q
and shorter τ

Theoretical Aspects

Case (i) : Purely monoenergetic neutrino

No positron emission

Consider ${}^{110}_{50}\mathrm{Sn}$

τ_{Sn} 4.11 hour

$$ {}^{110}_{50}\mathrm{Sn} + e^{-} \rightarrow {}^{110}_{49}\mathrm{In}^{*} + \nu_{e} $$

$$ Q = (638 - 343) - 28 = 267\mathrm{keV} $$

Mass difference Excited Energy Binding Energy

Neutrino Energy in rest frame

Acceleration of $^{110}_{50}\mathrm{Sn}$

$$\gamma_{\mathrm{Sn}} = \frac{\delta m^2 L}{8P}\frac{1}{Q_{\mathrm{Sn}}}$$

$$= 378\left(\frac{\delta m^2}{2.5\times 10^{-3}\mathrm{eV}^2}\right)\left(\frac{L}{100\mathrm{km}}\right)\left(\frac{\pi/2}{P}\right)\left(\frac{267\mathrm{keV}}{Q_{\mathrm{Sn}}}\right)$$

Baseline in the rest frame

$$L'_{\mathrm{Sn}} = 264\mathrm{m}\left(\frac{2.5\times 10^{-3}\mathrm{eV}^2}{\delta m^2}\right)\left(\frac{P}{\pi/2}\right)$$

$$\frac{L\ \text{independent}}{(Q\ \text{dependent})}$$

For $P = \frac{\pi}{3}$ Oscillation maximum is covered

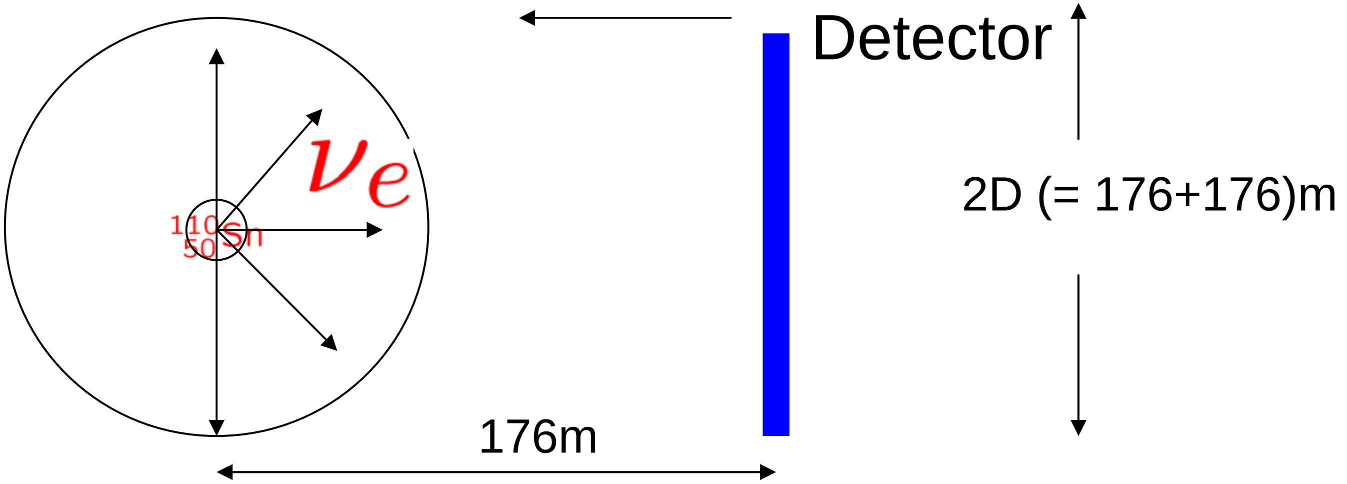
$$\gamma_{\mathrm{Sn}} = 567 \left(\frac{L}{100\mathrm{km}}\right)$$

$$\gamma_{\mathrm{Sn}}\tau_{\mathrm{Sn}} = 96 \left(\frac{L}{100\mathrm{km}}\right) \ \mathrm{days}$$ Lifetime in lab

$$L'_{\mathrm{Sn}} = 176\ \mathrm{m}$$ Baseline length in the rest frame

“All/2” ν_e hit a detector with diameter D=176m!

Rest frame of $^{110}_{50}\mathrm{Sn}$



Neutrino Energy as a function of *R*

Detector position from
beam center

$$E_\nu(R) = \frac{2\gamma m Q}{1 + R^2/L'^2}.$$

For a detector size *D*

$$\frac{2\gamma m Q}{1 + D^2/L'^2} < E_\nu < 2\gamma m Q,$$

For example $D = L'$

$$\gamma m Q \le E_\nu \le 2\gamma m Q$$

Very wide range of neutrino energy

Energy resolution

For the position resolution $\delta R (\delta R^2 = 2R\delta R)$

$\sim$ 30 cm for SK

Energy uncertainty is related with ***δR***

$$\left|\frac{\delta E_\nu}{E_\nu}\right| = \frac{\delta R^2/L'^2}{\left(1+R^2/L'^2\right)} < 10^{-4}.$$

Much better than others

Detection Position = Neutrino Energy !!

Energy Distribution

In a solid angle $d\Omega = 2\pi \sin\theta d\theta$ in rest frame

the number of neutrinos distribute uniformly

The solid angle is related with detector position

$$2\pi \sin\theta d\theta = \frac{4\pi}{\left(1 + R^2/L'^2\right)^2} \frac{dR^2}{L'^2} = \frac{2\pi}{\gamma_m Q} dE_\nu .$$

neutrino beam uniformly distributed in its energy

Optimum γ_m, baseline ? How large detector ?

Under consideration

Candidate Nucleus

Up to A=114

Mother, E^K	Daughter, E^K	Δ	τ	γ_m	$\tau\gamma_m$	Detector Size
${}^{110}_{50}$Sn ,29	${}^{110}_{49}$In* [343], 28	295	4.11 h	567	97 d	176 m
${}^{111}_{49}$In, 28	${}^{111}_{48}$Cd*[417], 27	449	2.80 d	359	1005 d	278m

Table 1: Nucleus candidates for case (i). γ_m is determined by $P = \pi/3$ for a detector at $L = 100$km and $\delta m^2 = 2.5 \times 10^{-3}$eV^2. The energy unit is keV. N*[E] means the excited state of the nucleus N with energy E[keV]. "Detector Size" indicates the radius within which a half of the emitted neutrinos are included at the detector distance.

Case (ii) : Monoenergetic and Continuous energy neutrino

If $Q > 2m_e$

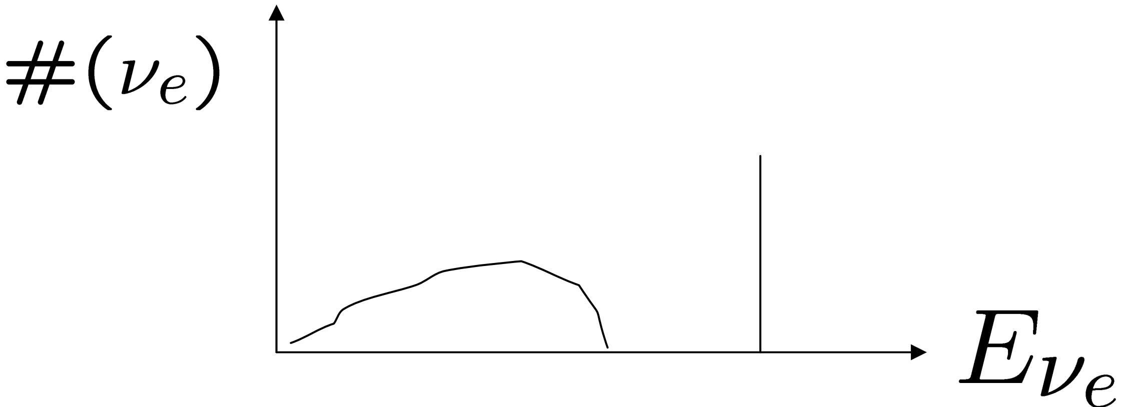
Both Electron capture and Positron Emission occur

Still Lower Q Nucleus

Mother, E^K	Daughter, E^K	Δ	τ	γ_m	$\tau\gamma_m$	EC	:	e^+emission
${}^{18}_{9}$F, 0.7	${}^{18}_{8}$O ,0.5	1656	110 m	61	4.65 d	3.4	:	96.6
${}^{48}_{24}$Cr, 6	${}^{48}_{23}$V*[420], 5	1239	21.56 h	82	74 d	98.0	:	2.0
${}^{111}_{50}$Sn ,29	${}^{111}_{49}$In, 28	2445	35.3 m	42	24.7 h	40.5	:	59.5
${}^{113}_{50}$Sn*[77], 29	${}^{113}_{49}$In, 28	1113	21.4 m	93	33.2 h	100	:	0

Table 1: Candidate Nuclei for case (ii). γ_m is determined by $P = \pi/2$ instead $\pi/3$.

Energy distribution
in rest frame



Q is high → γ_m is small

At a detector, neutrinos from EC are monoenergetic

$$E_{\nu_e} = 2\gamma_m Q$$

EC dominates in decay of $^{48}_{24}\mathrm{Cr}$ $^{113}_{50}\mathrm{Sn}^*$[77]

By varying γ_m

we can survey oscillation with definite energy resolution

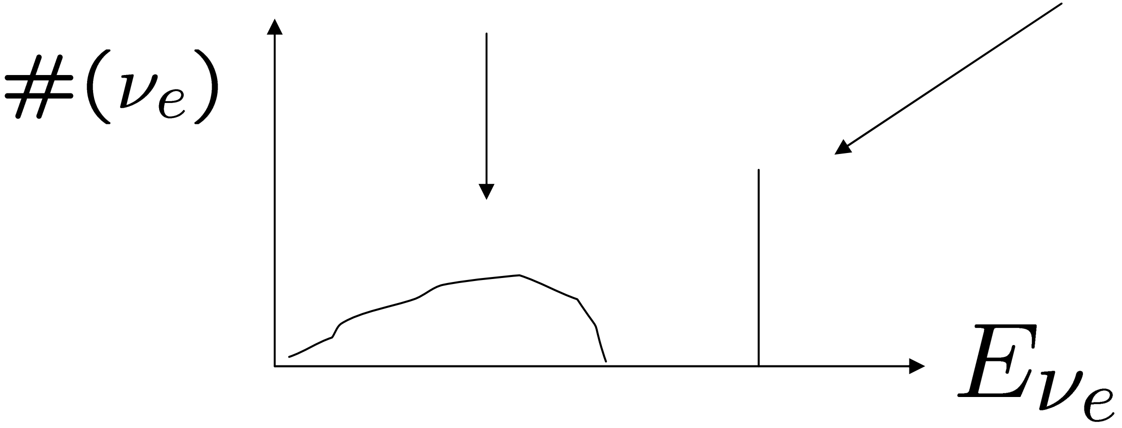
Optimum combination of γ_m's ?

EC and e^+ Emission almost half and half $^{111}_{50}\mathrm{Sn}$

Can we make use of

both line spectrum and continuum spectrum ?

Appropriate γ_m ?

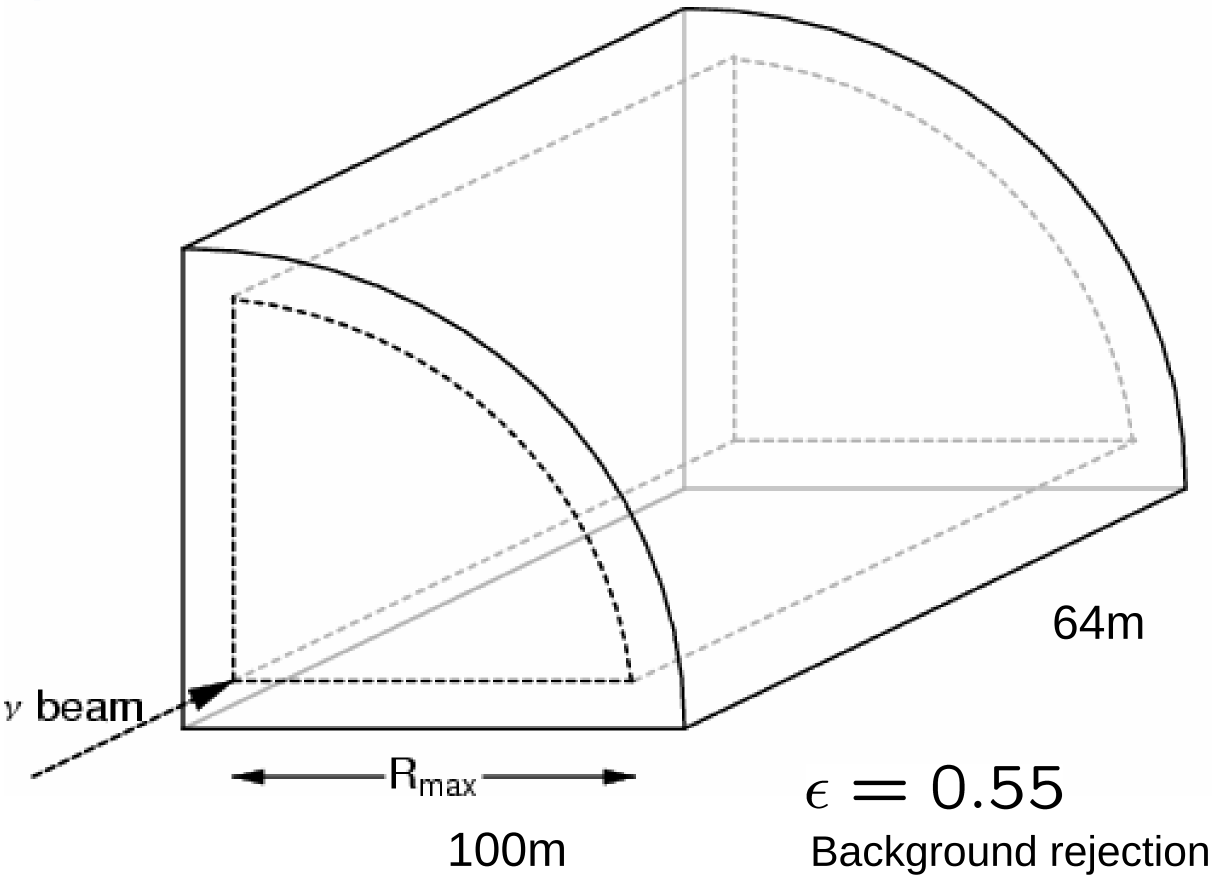


First maximum ?

Second maximum ?

3. Sensitivity for high γ scenario

Set Up $^{110}_{50}\mathrm{Sn} + e^- \rightarrow\ ^{110}_{49}\mathrm{In}^* + \nu_e$



$\epsilon = 0.55$

Background rejection 10^{-4}

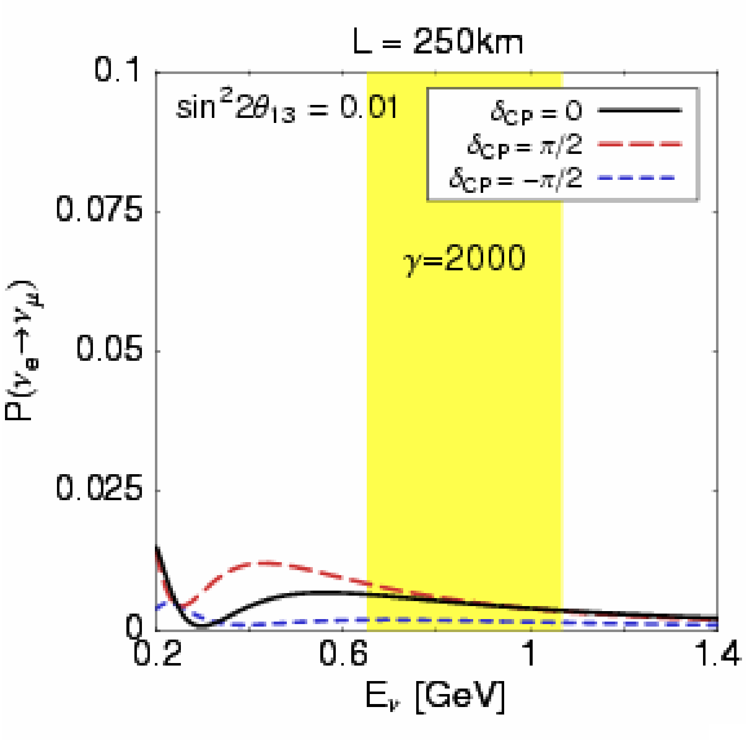
Systematical Uncertainty

Signal 2.5%
Background 5%

Fiducial 500kt

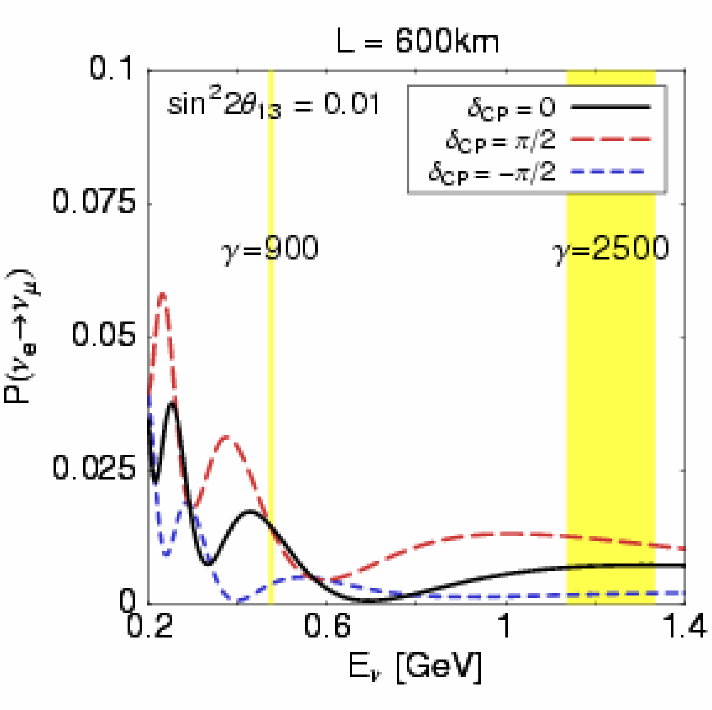
setupII

$L = 250\text{km}\ \gamma_m = 2000$



setupIII

$L = 600\text{km}\ \gamma_m = 900/2000$



$$\frac{2\gamma_m Q}{1+\gamma_m^2 R_{max}^2/L^2} < E_\nu < 2\gamma_m Q,$$

Input for “known” params

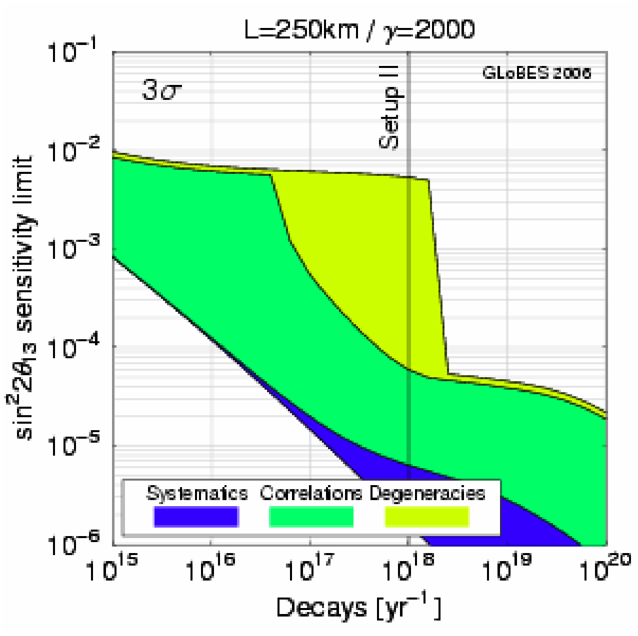
$$\Delta m_{31}^2 = 2.5 \times 10^{-3}\ \text{eV}^2\ \sin^2 2\theta_{23} = 1$$
$$\Delta m_{21}^2 = 8.2 \times 10^{-5}\ \text{eV}^2\ \sin^2 2\theta_{12} = 0.83$$

Sensitivity to $\sin^2 2\theta_{13}$

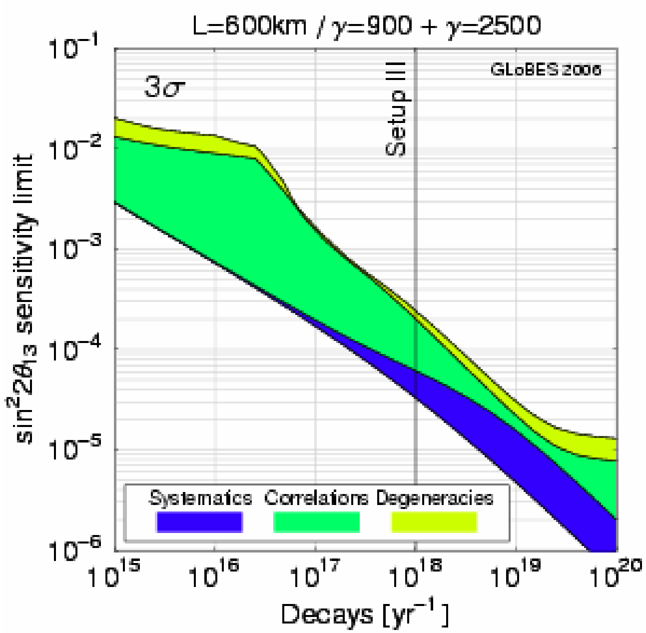
Test against the hypothesis $\sin^2 2\theta_{13} = 0$

CP Phase free, other params within corrent errors

Setup II



Setup III

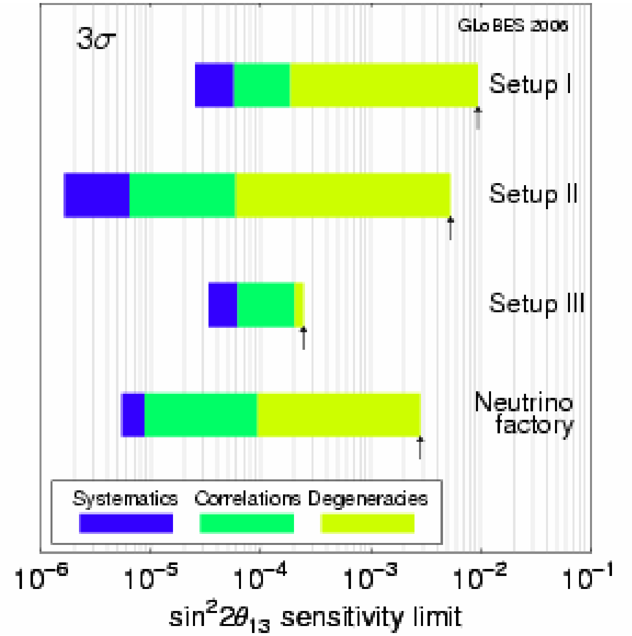


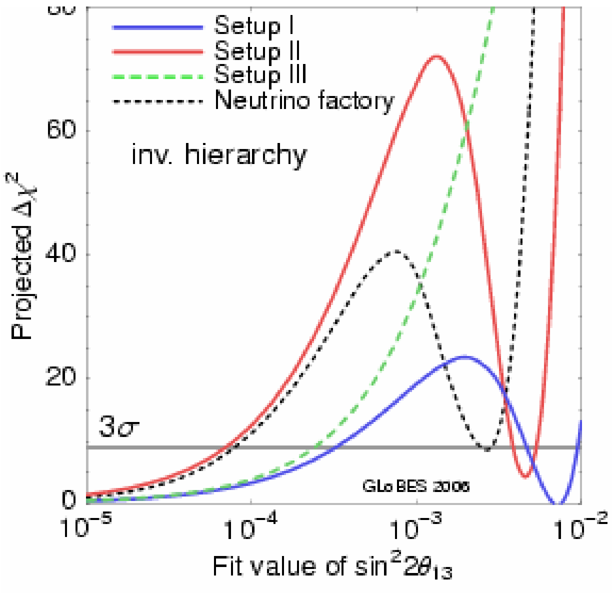
Better to observe the second maximum

As strongly emphasized in Arafune&Sato, Arafune&Koike&Sato

Comparison with NuFact 10^{21} decay /yr with 50kt MID

10^{18} decay / yr for monobeam with 500kt Water Cherenkov

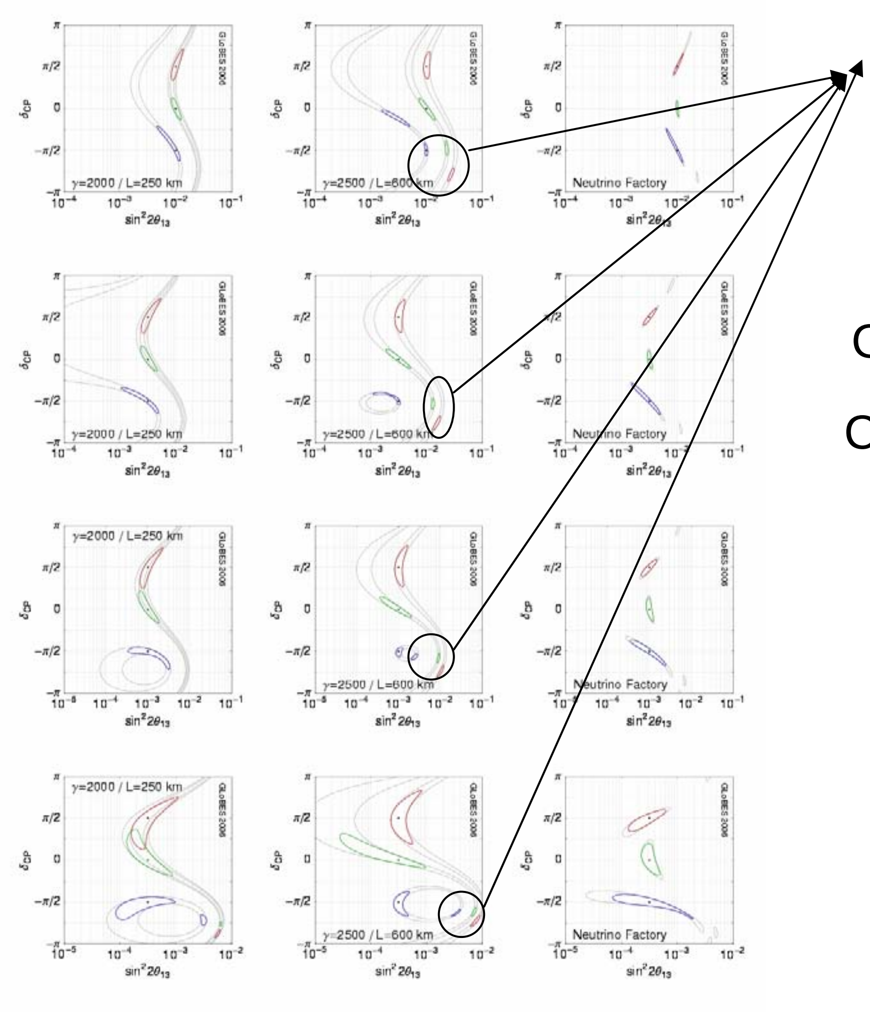




Importance of the second maximum

Set up II Set up I NuFact

Set up I = Setup III – second max $(\gamma = 900)$

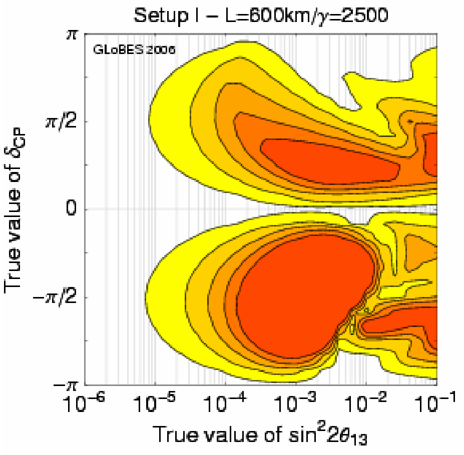


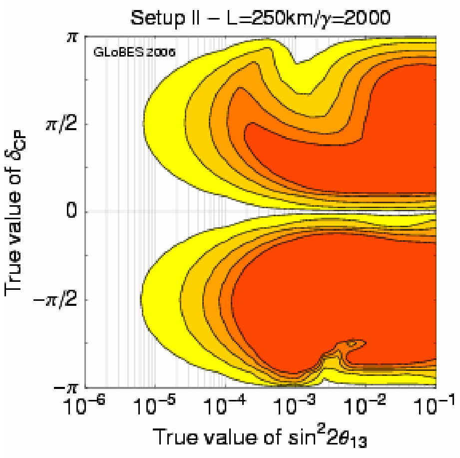
Degenerate solutions are removed by the information from second max

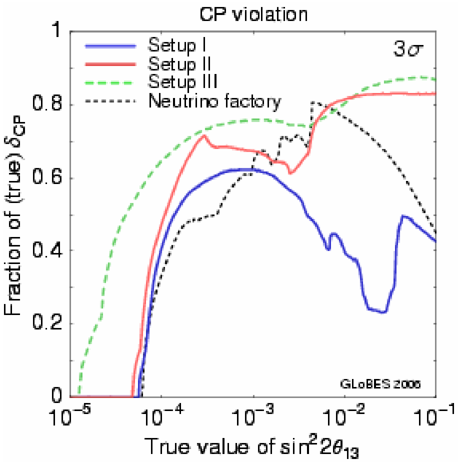
Gray lines : total rate only

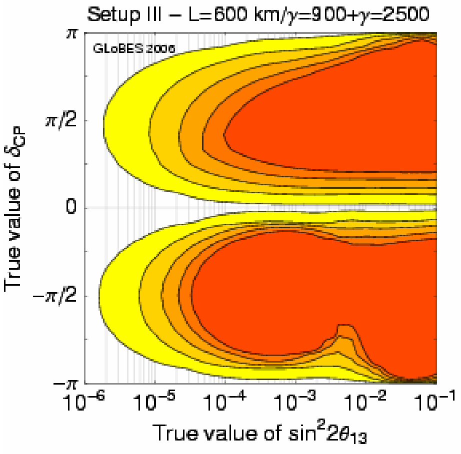
Colored lines : energy information used

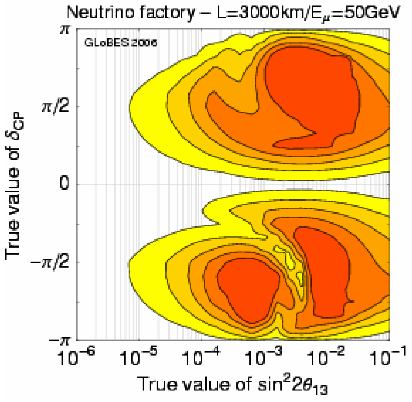
Sensitivity to δ_{CP}











Note : Naively there is no dependence on $\sin^2 2\theta_{13}$ In vacuum. Freund et al

See Setup III

4. Sensitivity for low γ scenario

NowCalculating

4. Summary and Discussion

Summary

Electron Capture :

Definite Neutrino Energy at rest frame Q

Control Neutrino Energy at lab
by boosting mother nuclei γ_m

For very low Q Very large γ_m

If large enough, almost all neutrinos hit a detector

Very efficient use of neutrinos

Very good “quality factor”

Furthermore we can survey very wide range of neutrino energy simultaneously and energy is extremely "measured" by the detector position

$$E_\nu(R) = \frac{2\gamma m Q}{1 + R^2/L'^2}.$$

Neutrino energy as a function of detector position

⇓

Simultaneous experiment with definite energy

Position is determined very precisely

Can we remove backgrounds more efficiently !?

Compare

0.1% (nufact) neutrinos are used

10^{18} ${}^{110}_{50}\mathrm{Sn}$ will give better sensitivity than NuFact

Can we reduce “life time” for electron capture ?

Maybe …, Nomura, J.S. Shimomura hep-ph/0605031

For not low $Q > 2m_e$

Both Electron capture and Positron Emission occur

EC dominates in decay of $^{48}_{24}\mathrm{Cr}$ $^{113}_{50}\mathrm{Sn}^*[77]$

Monoenergetic Neutrino at a detector due to lower γm

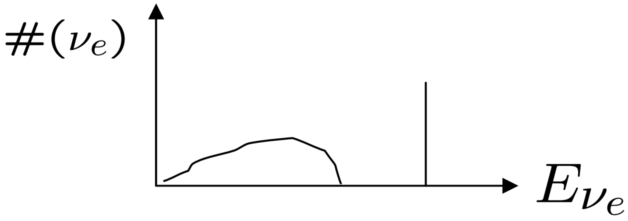
$2\gamma m Q$

By varying γm

we can survey oscillation with definite energy resolution

EC and e^+ Emission almost half and half $^{111}_{50}\mathrm{Sn}$

Efficient γm ?



Making use of both continuous and line spectrum?

Problems

CP/T conjugate channels?

How to create anti-neutrino beam ?

How to create muon-neutrino beam ?

Otherwise

Rely on parameter fitting?

Or Controll pions??