Activities in Long Baseline Neutrino oscillations in China

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Contents

- LBL physics study
  - Optimum baseline
  - Physics potential
  - Density effects
- Detector: Water Cerenkov Calorimeter
- site

- **We Know Now**

  $|\Delta m^2_{32}|$, $\sin^2 2\theta_{32}$ ---- SuperK

  Δm^2_{21}, $\sin^2 2\theta_{21}$ ---- KamLAND,SNO

- **We Want to Know in future**

  $\sin^2 2\theta_{13}$, $\pm\Delta m^2_{32}$, δ

  ---- ν factory/beam

Oscillation Probabilities

$$P(\nu_e \rightarrow \nu_\mu) \simeq s_{23}^2 sin^2 2\theta_{13} sin^2 \frac{\Delta m_{23}^2 L}{4E} * F_1(A) + F_2(A, \delta, sin^2 2\theta_{21}, \Delta m_{12}^2)$$

$$P(\nu_e \rightarrow \nu_\tau) \simeq c_{23}^2 sin^2 2\theta_{13} sin^2 \frac{\Delta m_{23}^2 L}{4E} * F_3(A) + F_4(A, \delta, sin^2 2\theta_{21}, \Delta m_{12}^2)$$

$$P(\nu_\mu \rightarrow \nu_\tau) \simeq c_{13}^4 sin^2 2\theta_{23} sin^2 \frac{\Delta m_{23}^2 L}{4E} * F_5(A) + F_6(A, \delta, sin^2 2\theta_{21}, \Delta m_{12}^2)$$

For $\nu_\mu \rightarrow \nu_e$: $\quad \delta \rightarrow -\delta$

For $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$: $\quad \delta \rightarrow -\delta, \quad A \rightarrow -A$

Assuming 3 generations, $\Delta m_{12}^2 << \Delta m_{23}^2$, $\Delta m_{13}^2 = \Delta m_{23}^2$

What is the optimum baseline ?

A Simple Exercise:

$$\Delta m^2_{32} = \Delta m^2_{31} = 3 \times 10^{-3}\ \mathrm{eV}^2$$

$$\Delta m^2_{21} = 5 \times 10^{-5}\ \mathrm{eV}^2$$

$$\sin^2 2\theta_{32} = \sin^2 2\theta_{21} = 1$$

$$\theta_{31} = 7^\circ$$

$$\delta = 90^\circ$$

$$A = 2.3 \times 10^{-4}\ \mathrm{eV}^2/\mathrm{GeV}$$

Y.F. Wang et. al, PRD Phys. Rev. D65 (2002) 073006

Neutrino statistics

$$N = A\Phi(E, L)\sigma(E)P(E, L)$$

Neutrino flux at ν factories:

$$\Phi(E, L) \propto \frac{E^2}{L^2}$$

Neutrino flux at conventional ν beams:

$$\frac{d\sigma}{dP d\Omega} \propto \frac{E(1 - 2E/E_p)^A (1 + 5e^{-2DE/E_p})}{(1 + p_t^2/C)^4}$$

Neutrino CC cross section:

$$\sigma(E) \propto E$$

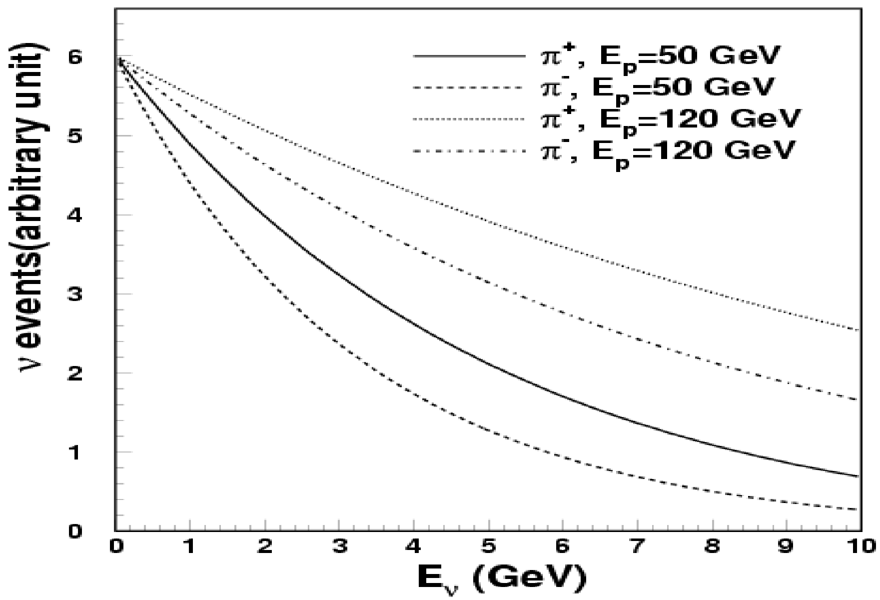
Oscillation probability:

$$P(E, L) \propto F(L/E)$$

At L/E fixed:

$N \propto E$ for ν factories

$N \propto (1 - 2E/E_p)^A (1 + 5e^{-2DE/E_p})$ for ν beams



A=2.5, C=0.58, D=3.1 for π^+, A=3.5, C=0.69, D=5.0 for π^-

Error on the Oscillation Probability

$$
\begin{aligned}
P &= \frac{N_s}{A\phi\sigma} \\
d^2P &= \frac{d^2N_s}{A^2\Phi^2\sigma^2} + \frac{N_s^2 d^2\Phi}{A^2\Phi^4\sigma^2} + \frac{N_s^2 d^2\sigma}{A^2\Phi^2\sigma^4} \\
d^2N_s &= d^2(N - N_b) = d^2N + d^2N_b \\
&= N_s + N_b + r^2N_b^2 \\
&= PA\Phi\sigma + fA\Phi\sigma + r^2f^2A^2\Phi^2\sigma^2 \\
d^2P &= \frac{P+f}{A\Phi\sigma} + r^2f^2 + P^2\left(\frac{d^2\Phi}{\Phi^2} + \frac{d^2\sigma}{\sigma^2}\right)
\end{aligned}
$$

Typically

$f \sim 0.02$ ——— Background fraction from Detector

$f \sim 0.01$ ——— Background fraction from beam

$r \sim 0.1$ ——— Uncertainty on background

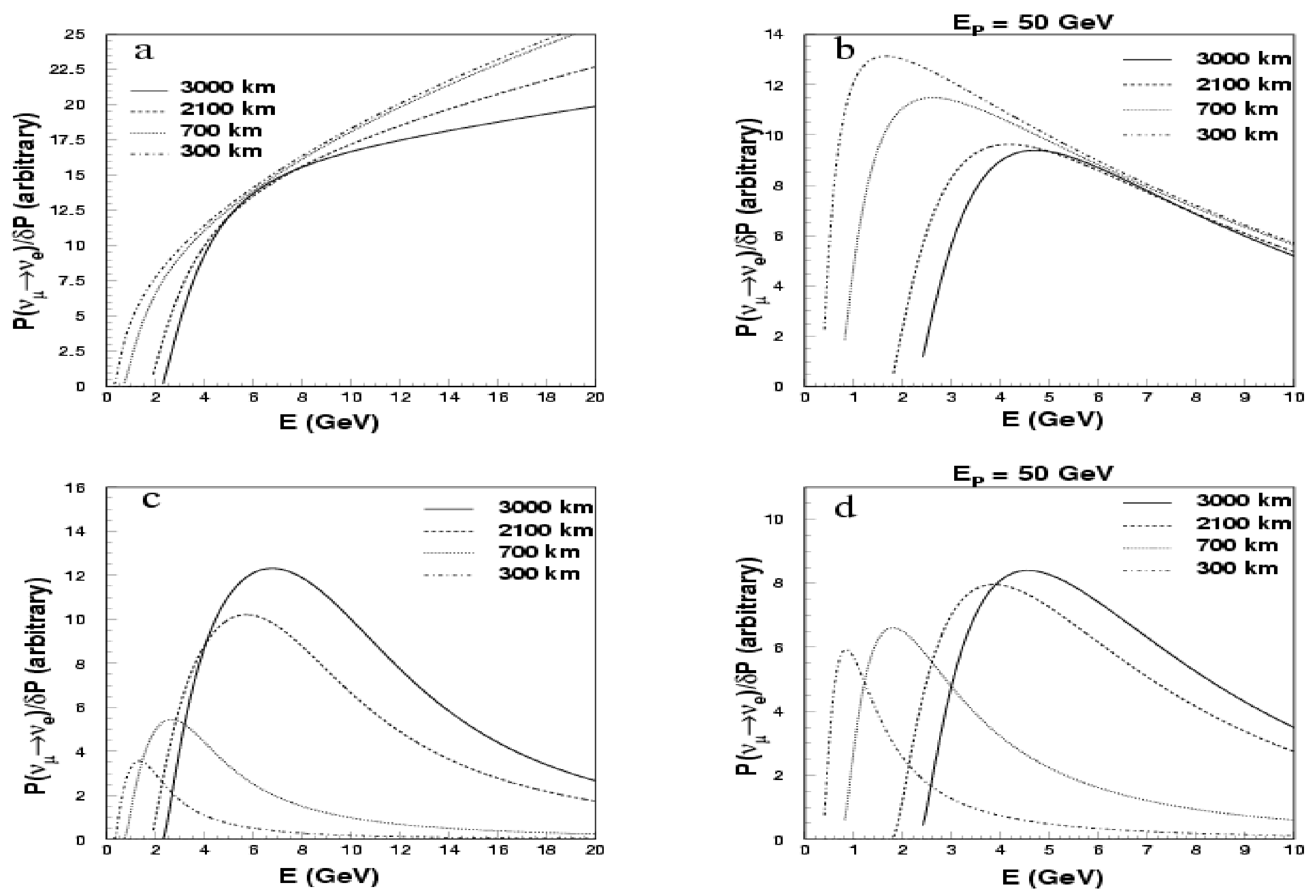
$\frac{d\Phi}{\Phi} \sim 0.01$ ——— Uncertainty on flux

$\frac{d\sigma}{\sigma} \sim 0.05$ ——— Uncertainty on cross section

Measurement of $sin\theta_{13}$

$$\frac{P}{dP} = \frac{P}{\sqrt{\frac{P+f}{A\Phi\sigma} + r^2 f^2 + P^2\left(\frac{d^2\Phi}{\Phi^2} + \frac{d^2\sigma}{\sigma^2}\right)}}$$

Neutrino factory | **meson-neutrino beam**

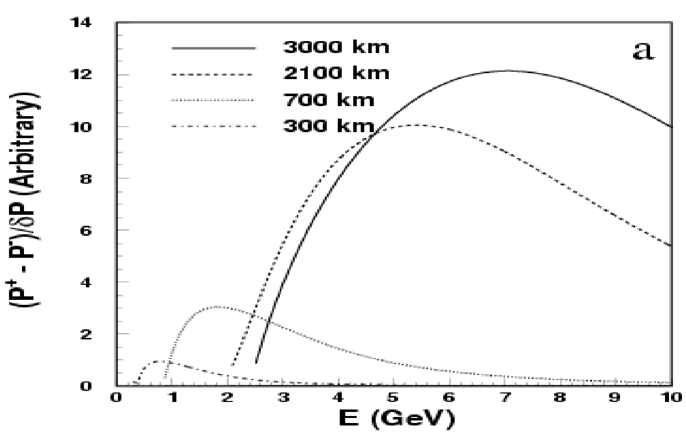


Sign of Δm^2_{23}

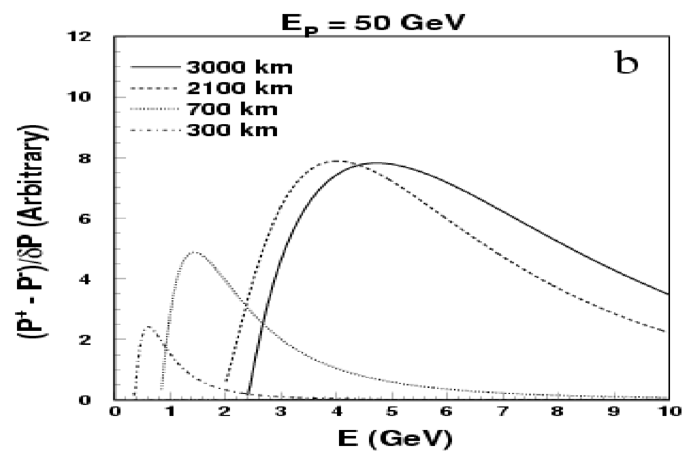
$$g^2 = \frac{d\Phi^2}{\Phi^2} + \frac{d\sigma^2}{\sigma^2}$$

$$\frac{P_+ - P_-}{dP} = \frac{P_+(\nu_\mu \to \nu_e) - P_-(\nu_\mu \to \nu_e)}{\sqrt{\frac{P_+ + f}{A\Phi\sigma} + r^2 f^2 + P_+^2 g^2}}$$

Neutrino factory



meson-neutrino beam



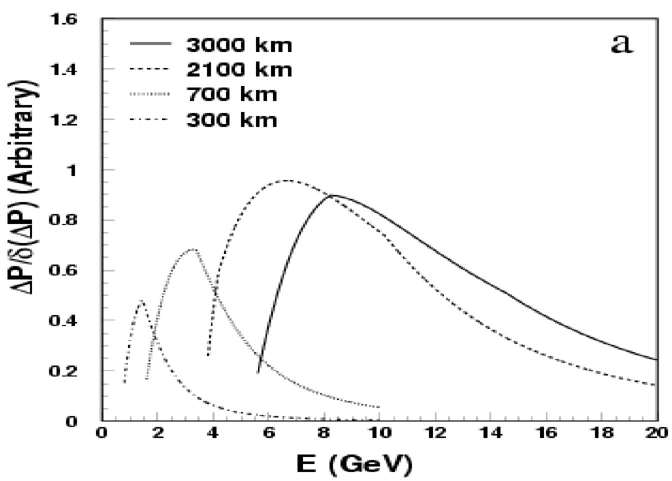
Leptonic CP phase δ

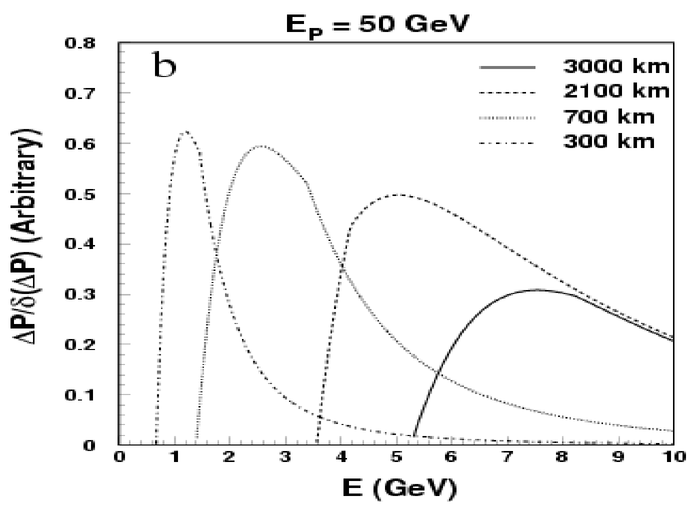
$$\Delta \mathrm{P} = \mathrm{P}(\nu_\mu \to \nu_\mathrm{e}) - \mathrm{P}(\bar{\nu}_\mu \to \bar{\nu}_\mathrm{e}) \equiv \mathrm{P}_1 - \mathrm{P}_2$$

$$\frac{\Delta P(\delta) - \Delta P(\delta = 0)}{d(\Delta P)} = \frac{\Delta P(\delta) - \Delta P(\delta = 0)}{\sqrt{dP_1^2 + dP_2^2}}$$

$$= \frac{\Delta P(\delta) - \Delta P(\delta = 0)}{\sqrt{\frac{P_1 + f}{A_1 \Phi_\nu \sigma_\nu} + 2r^2 f^2 + \frac{P_2 + f}{A_2 \Phi_{\bar{\nu}} \sigma_{\bar{\nu}}} + P_1^2 g_1^2 + P_2^2 g_2^2}}$$

Neutrino factory **meson-neutrino beam**



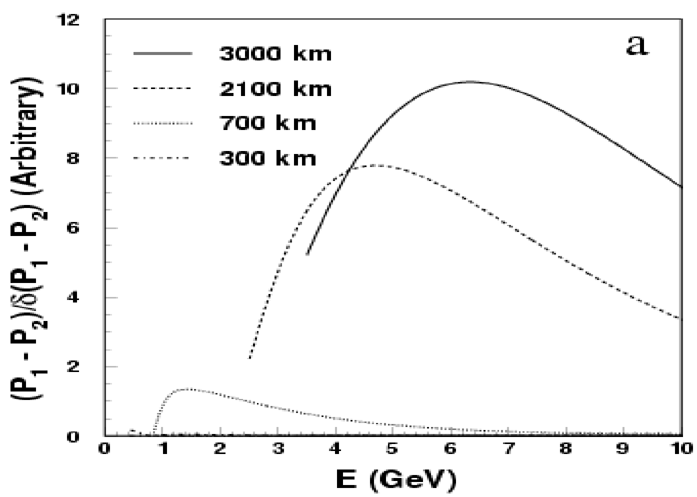


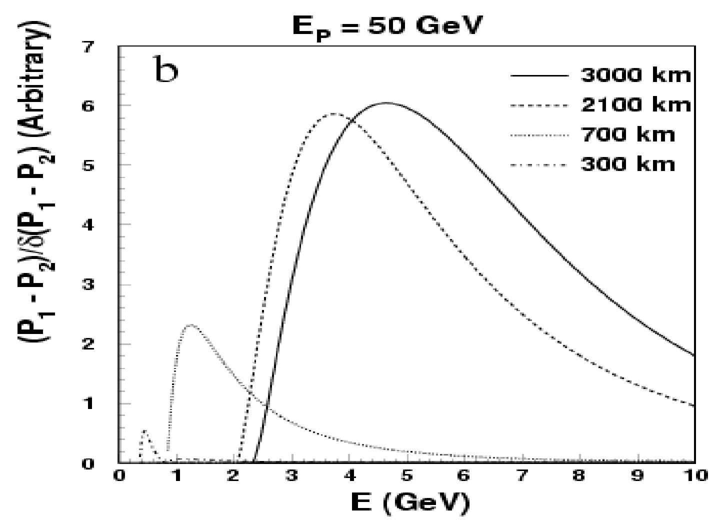
Matter Effect

$$\mathrm{P}_1 = \mathrm{P}(\nu_\mu \to \nu_\mathrm{e}), \quad \mathrm{P}_2 = \mathrm{P}(\bar{\nu}_\mu \to \bar{\nu}_\mathrm{e})$$

$$\frac{P_1 - P_2}{\delta(P_1 - P_2)} = \frac{P_1 - P_2}{\sqrt{\frac{P_1+f}{A_1\Phi_\nu\sigma_\nu} + 2r^2f^2 + \frac{P_2+f}{A_2\Phi_{\bar{\nu}}\sigma_{\bar{\nu}}} + P_1^2g_1^2 + P_2^2g_2^2}}$$

Neutrino factory **meson-neutrino beam**

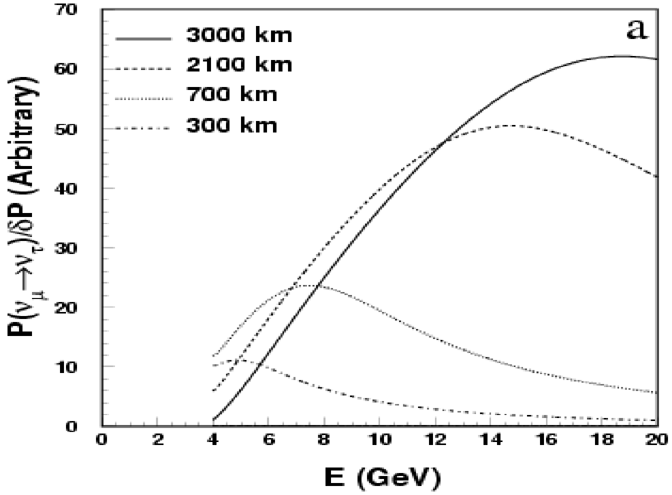




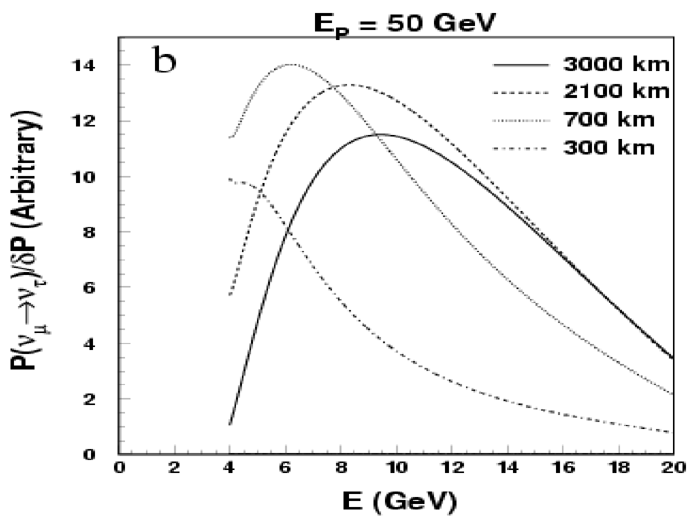
Tau appearance

$$\frac{P(\nu_\mu \to \nu_\tau)}{dP(\nu_\mu \to \nu_\tau)} = \frac{P}{\sqrt{\frac{P+f}{A\Phi\sigma} + r^2 f^2 + P^2 g^2}}$$

Neutrino factory



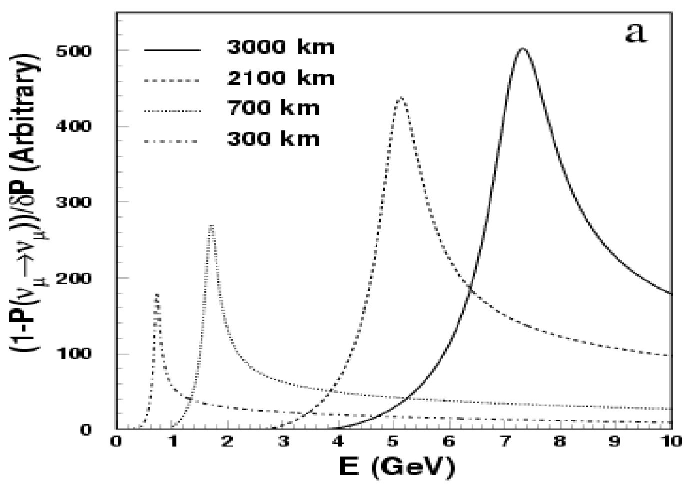
meson-neutrino beam

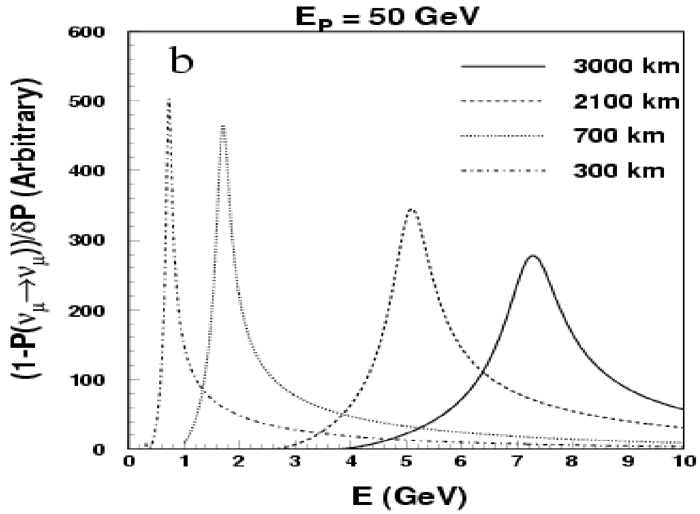


Precision Measurement of Δm^2_{23} and $sin^2 2\theta_{23}$

$$\frac{1 - P(\nu_\mu \to \nu_\mu)}{dP(\nu_\mu \to \nu_\mu)} = \frac{(1-P)}{\sqrt{\frac{P+f}{A\Phi\sigma} + r^2 f^2 + P^2 g^2}}$$

Neutrino factory **meson-neutrino beam**





Summary

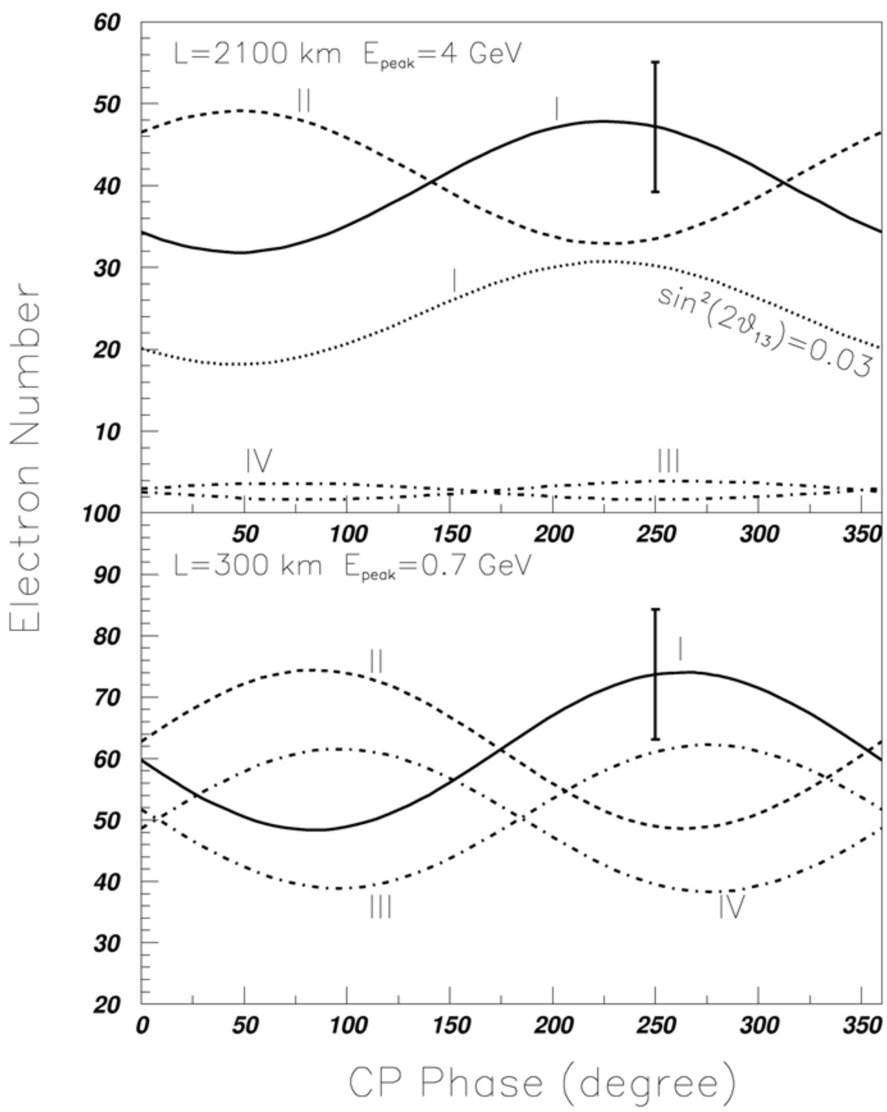
	neutrino factory		meson-neutrino beam	
	300 km	2100 km	300 km	2100 km
$\sin^2 2\theta_{13}$	3.5	10.5	6.0	8.0
CP phase δ	0.5	0.95	0.62	0.5
sign of Δm^2_{32}	1.0	10.	2.5	8.0
matter effects	0.2	8.	0.5	6.0
Δm^2_{32} and $\sin^2 2\theta_{23}$	180	450	500	350
τ appearance	10	50	9.5	13.5

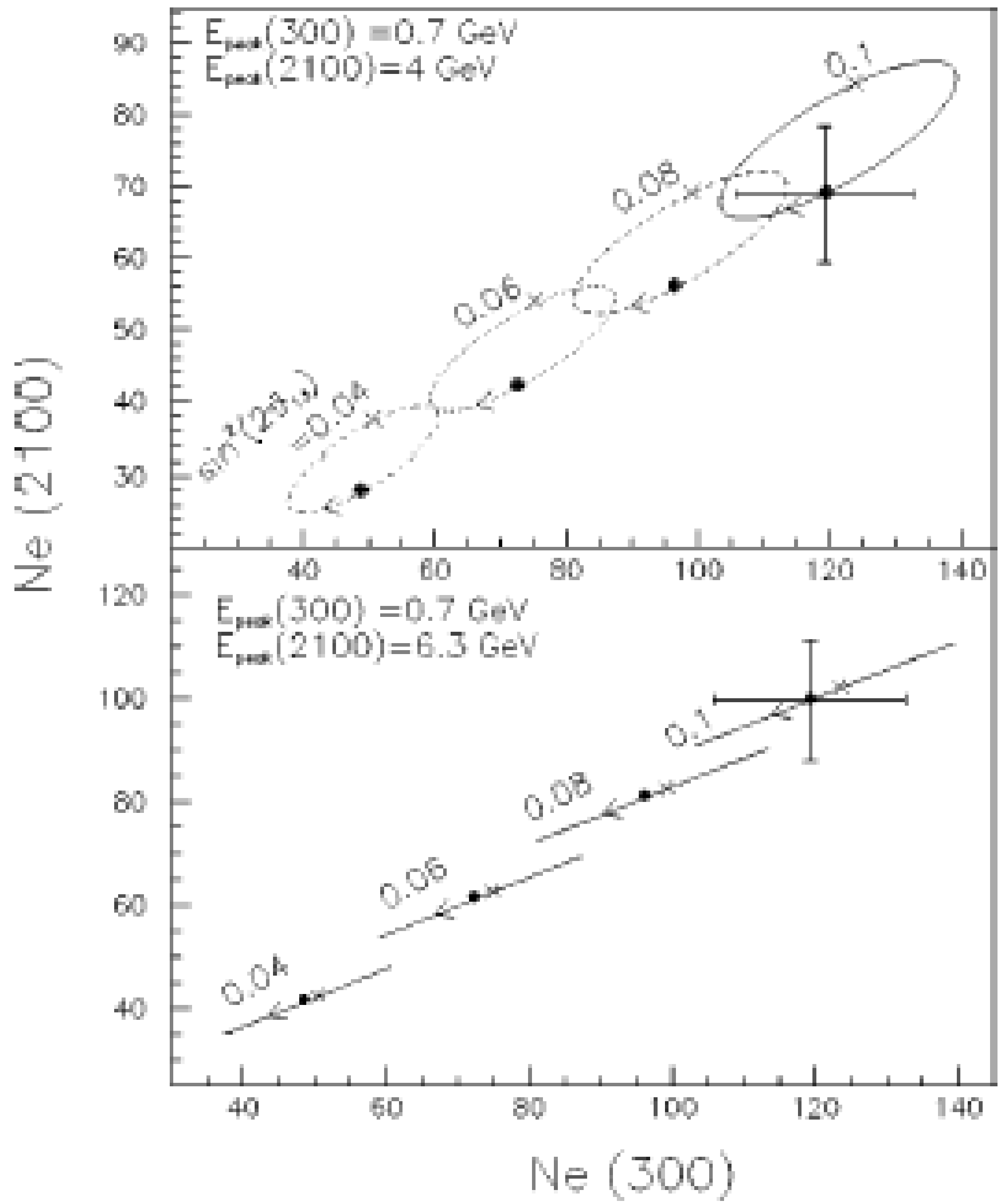
Study of LBL physics capabilities:

Determine mass hierarchy

	I	II	III	IV
Δm^2_{12}	+	−	+	−
Δm^2_{23}	+	+	−	−

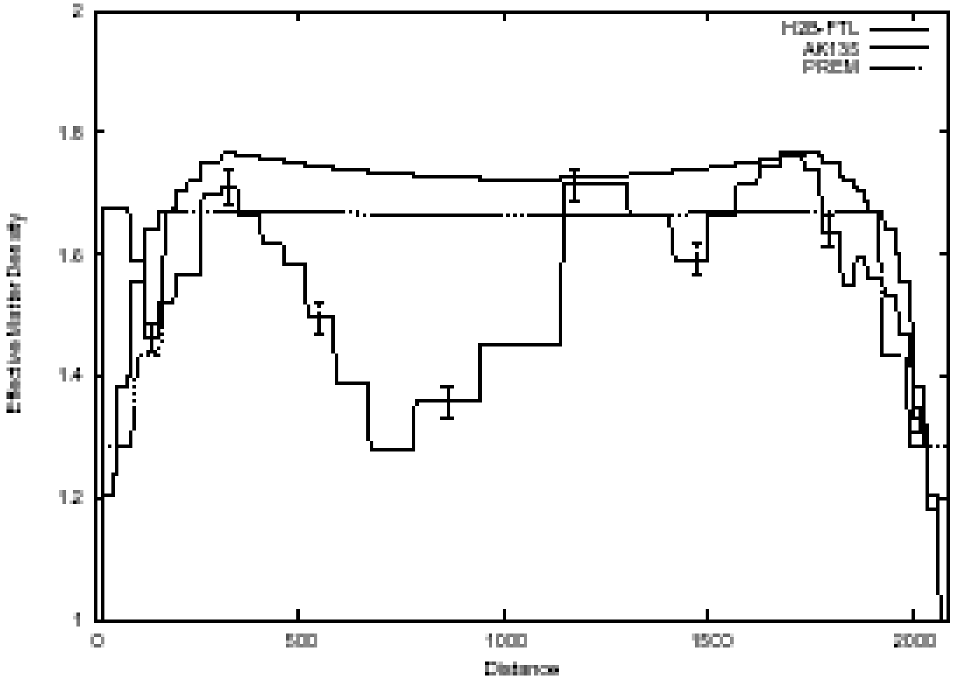
Y-F. Wang et al.,
Phys. Rev. D65 (2002) 073021

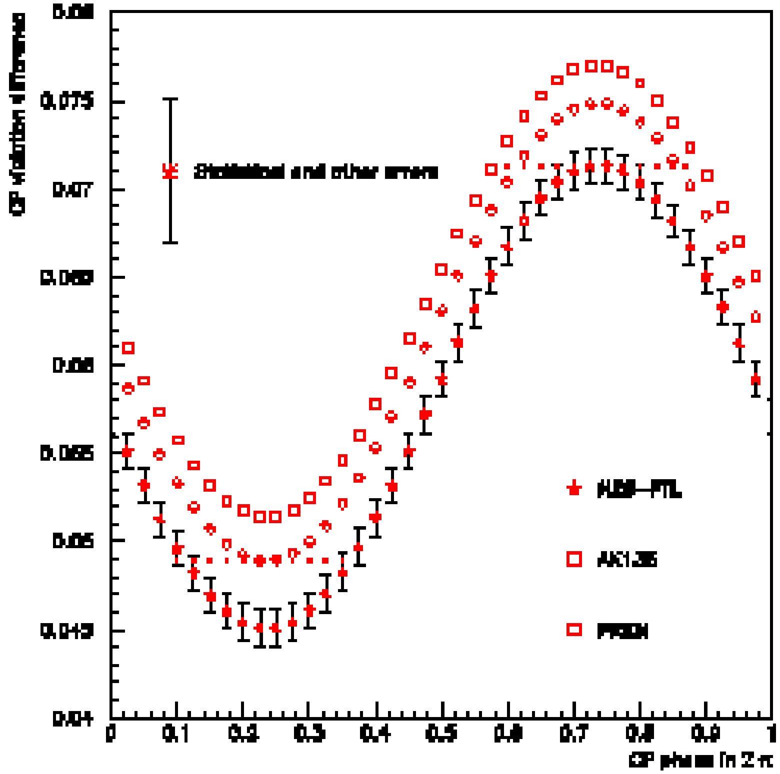




E_peak(300) =0.7 GeV
E_peak(2100)=4 GeV
sin²(2θ_μ)
=0.04
0.06
0.08
0.1
E_peak(300) =0.7 GeV
E_peak(2100)=6.3 GeV
0.04
0.06
0.08
0.1
Ne (2100)
Ne (300)

Study of density effects:





Lian-You Shan et al., Phys. Rev. D 68 (2003) 013002

Large volume detector: Water Cerenkov calorimeter

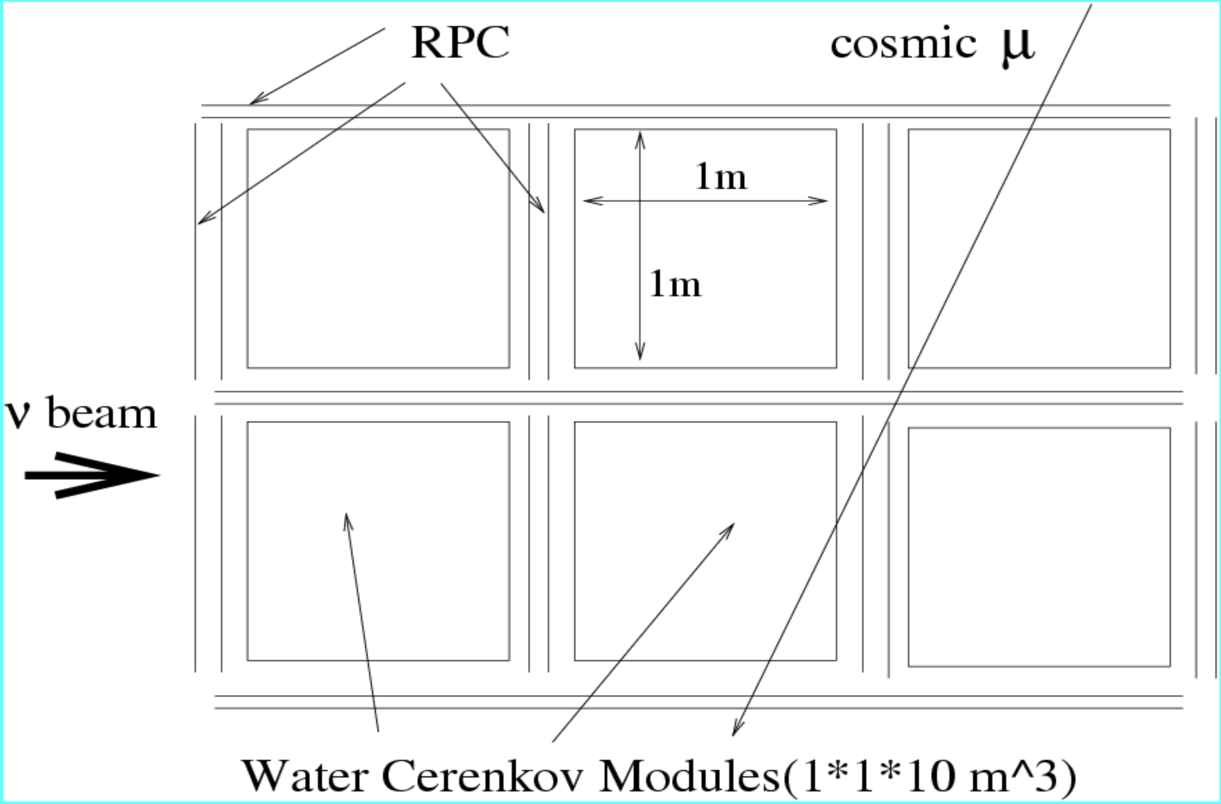
Water Cerenkov Calorimeter

Dimensions:

$40\times20\times125$ m^3

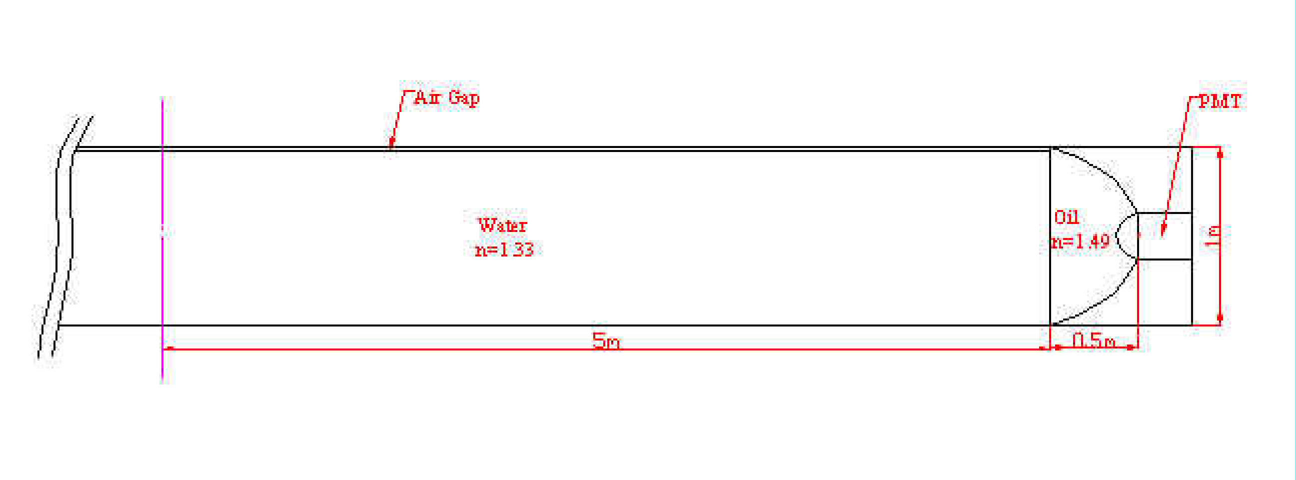
Each cell:
$1\times1\times10$ m^3

10,000 tanks => 100Kt



Segmentation to be optimized depending on the ν beam, experimental hall, price, ...

PVC Water tanks with Reflective **lining, viewed by two 8” PMT/tank**



Cerenkov light yield: 20,000 photons/meter

For 10 m attenuation length, 90% reflection eff.

Light collection eff.	15%
Cone collection eff.	5%
PMT Quantum eff.	20%
Total	0.15%

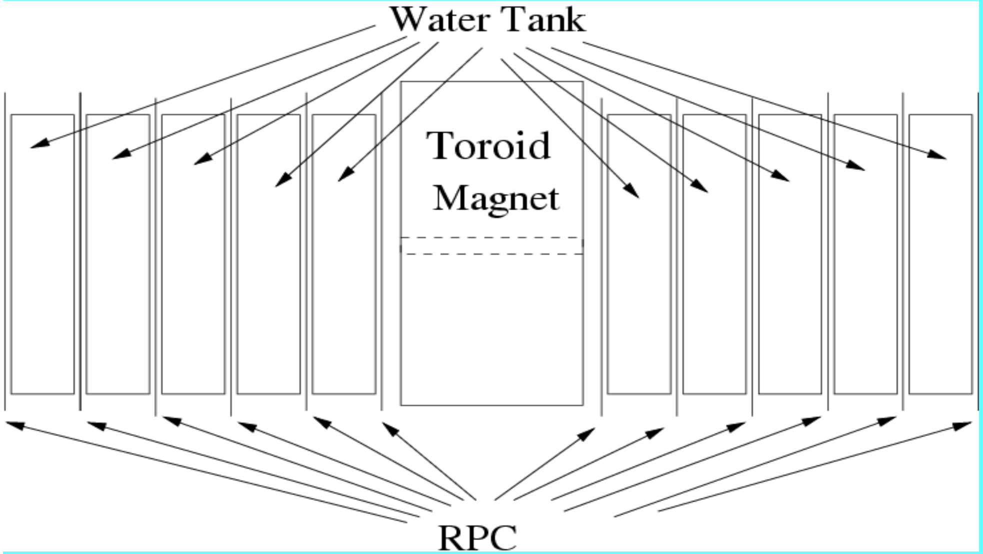
For through-going muons, 30 PE/Tank

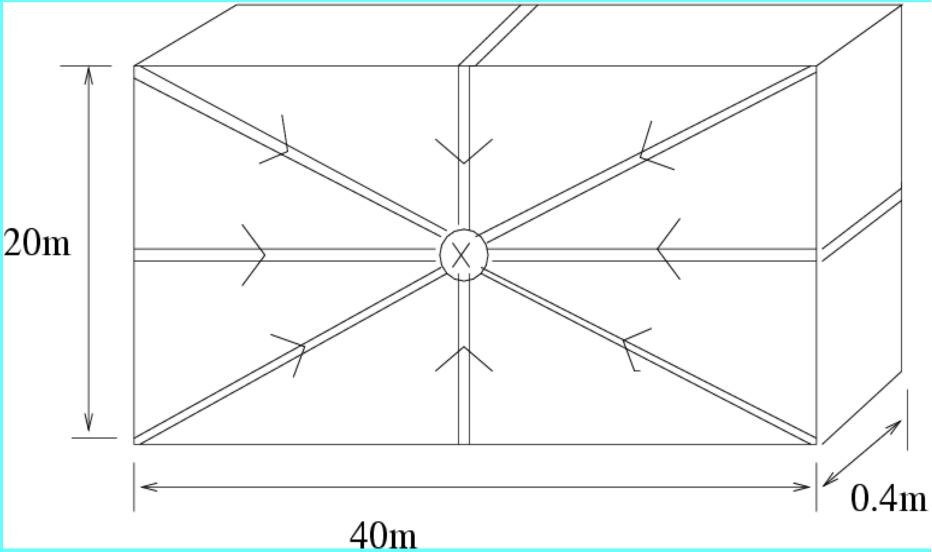
$$1 \text{ m water} = 2.77\, X_0 = 1.5\, \lambda_0$$

Typical numbers

- $30 \times 10 \times 300\ m^3$
- 10,000 water tanks
- 20,000 8” PMT/readout channels
- 100,000 m^2 RPC
- 50,000 chambers

Toroid Magnet





IF P^{μ}_{min} = 5 GeV, we need 40 cm thick steel plate as magnet for every 20 m, a total of 6 magnet segments

Total magnet weight: 16 kT

A Simple Exercise:

$\Delta m^2_{32} = \Delta m^2_{31} = 3 \times 10^{-3}$ eV^2

$\Delta m^2_{21} = 5 \times 10^{-5}$ eV^2

$\sin^2 2\theta_{32} = \sin^2 2\theta_{21} = 1$

$\sin^2 2\theta_{31} = 0.059$

$\delta = 0$

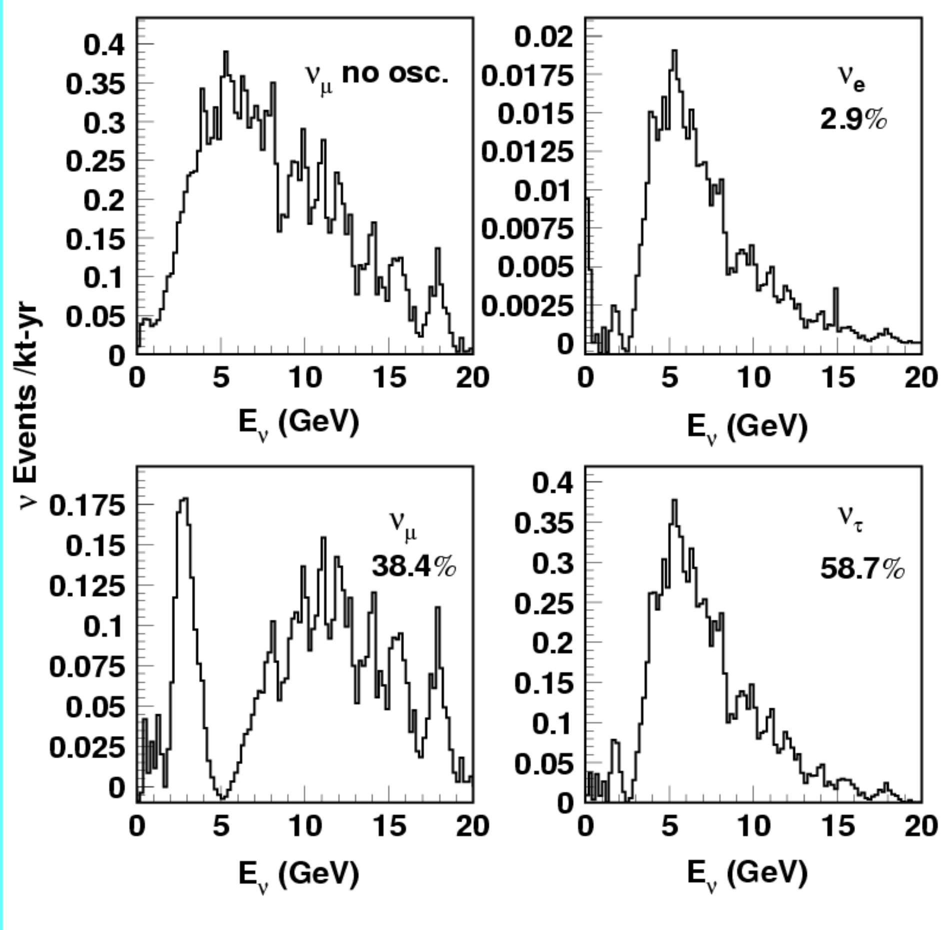
$A = 1 \times 10^{-4}$ eV^2 /GeV

Two Scenarios considered for the near future:

A) JHF(HIPA) to Beijing

L=2100 km

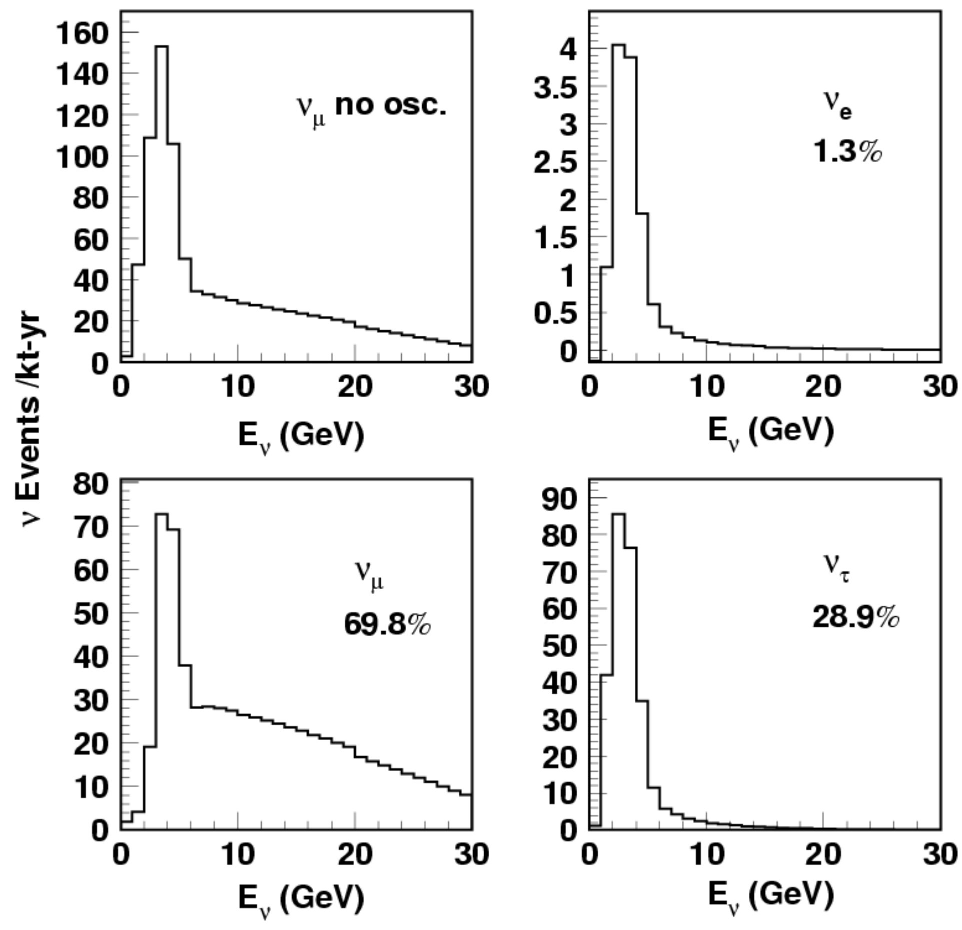
1300 events/100kt-Yr



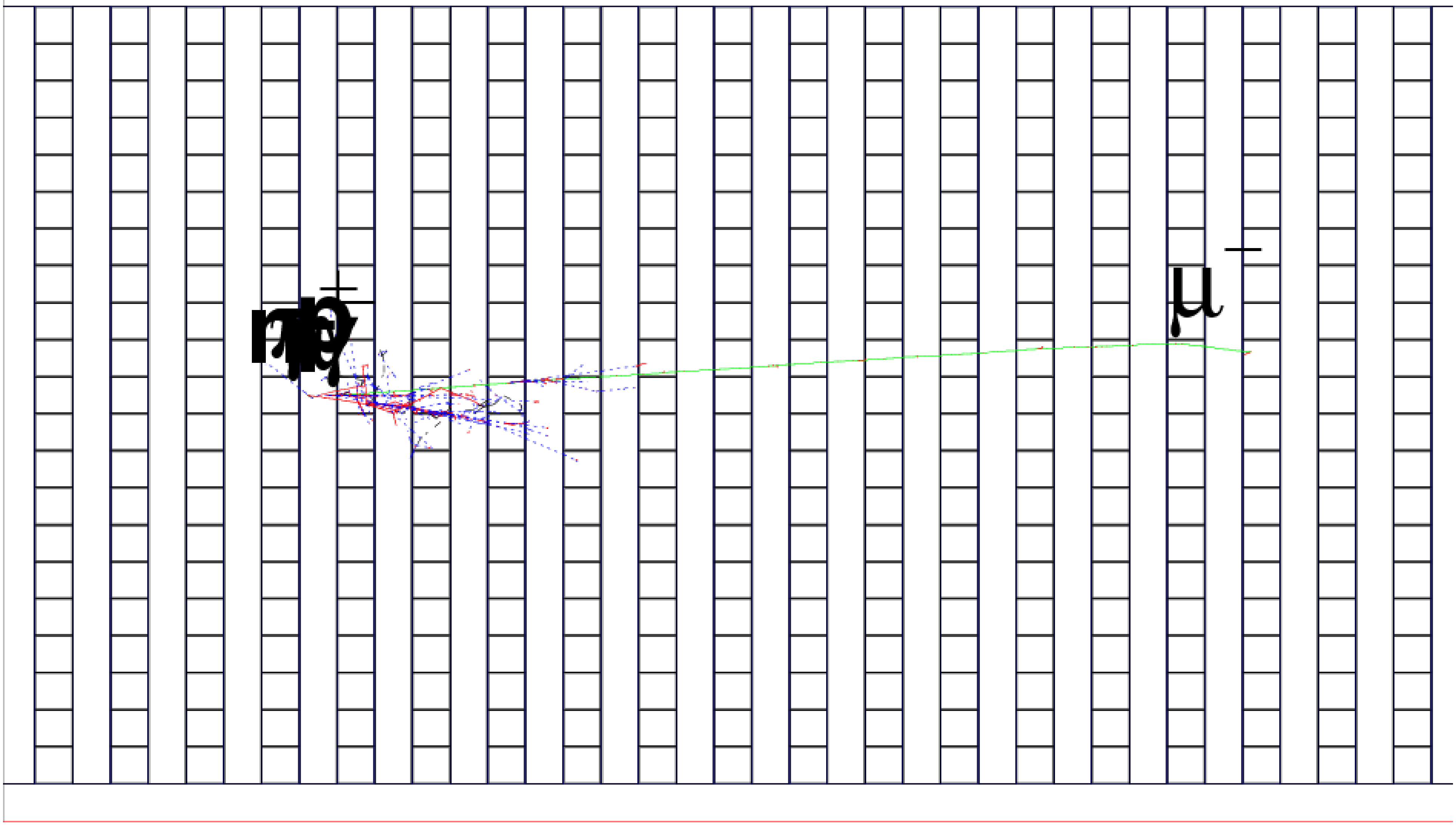
B) Fermilab to Minos

L=735 km

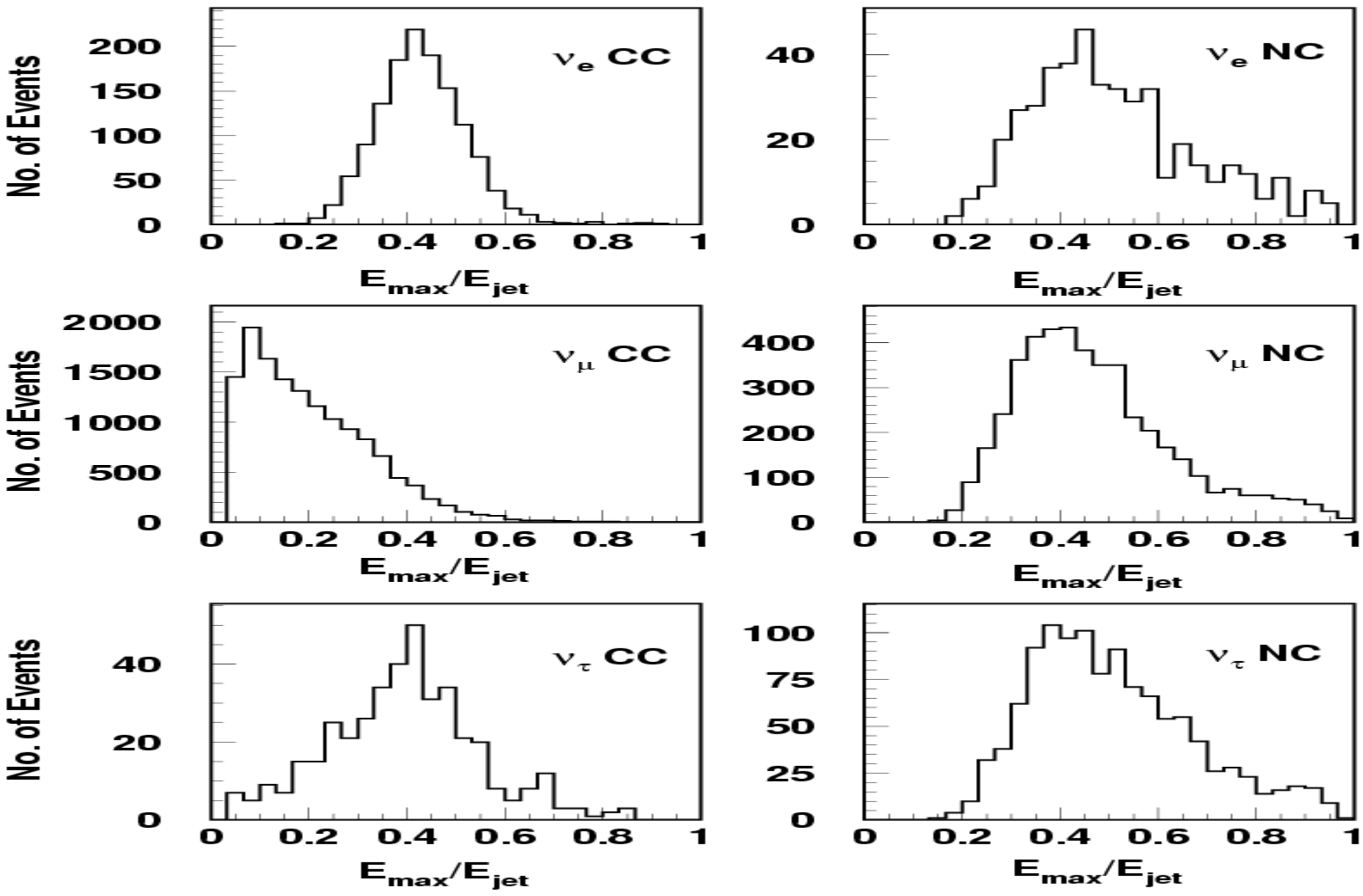
45K evts/100kt-Yr



A typical ν_μ CC event



ν_e Selection: Maximum energy in a cell

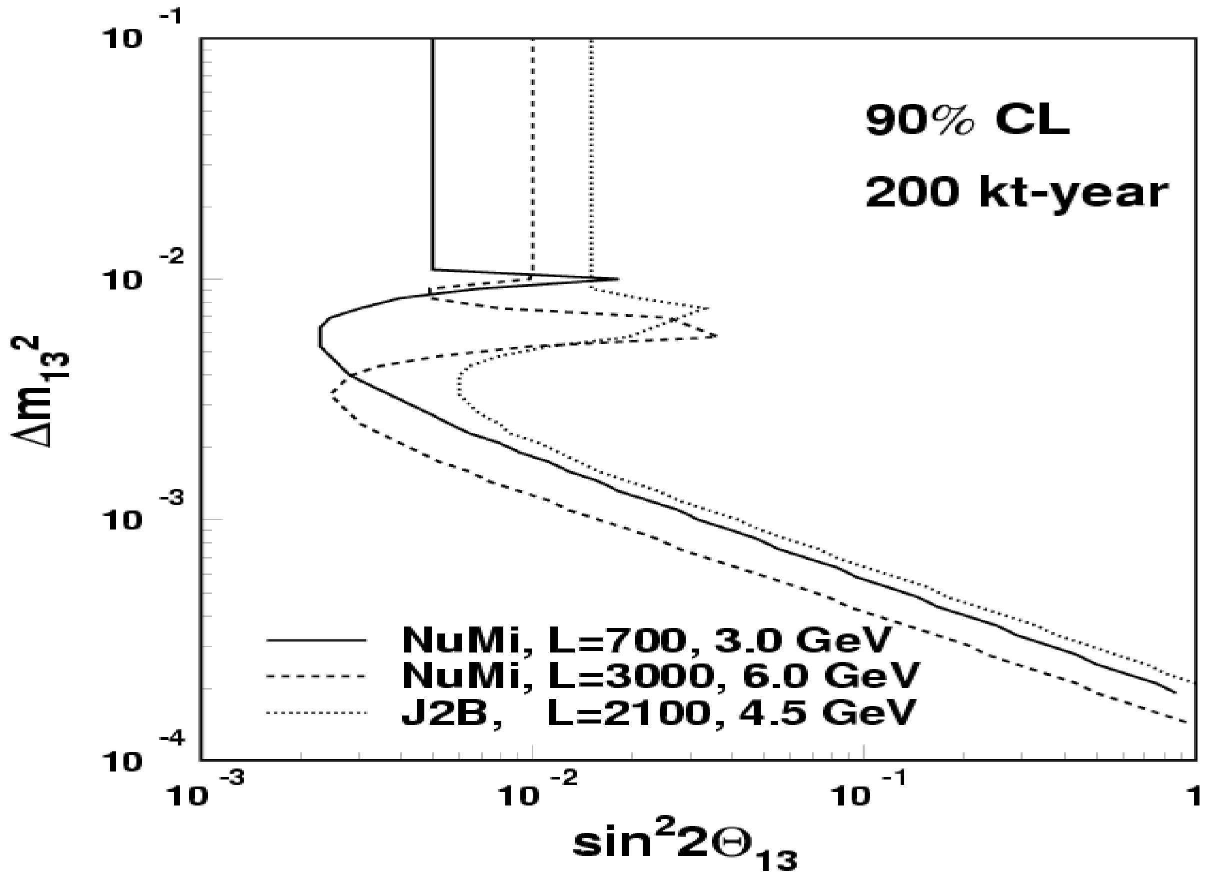


Results from full Monte Carlo simulation

	JHF-Beijing			NuMi-Minos	
	ν_e	ν_μ	ν_τ	ν_e	ν_μ
CC Eff.	30%	53%	9.3%	15%	53%
ν_e CC	-	$>$1300:1	3:1	-	$>$1300:1
ν_e NC	166:1	665:1	60:1	600:1	$>$610:1
ν_μ CC	700:1	-	270:1	14000:1	-
ν_μ NC	92:1	$>$6000:1	39:1	320:1	2000:1
ν_τ CC	20:1	12:1	-	33:1	18:1
ν_τ NC	205:1	1100:1	61:1	530:1	3200:1

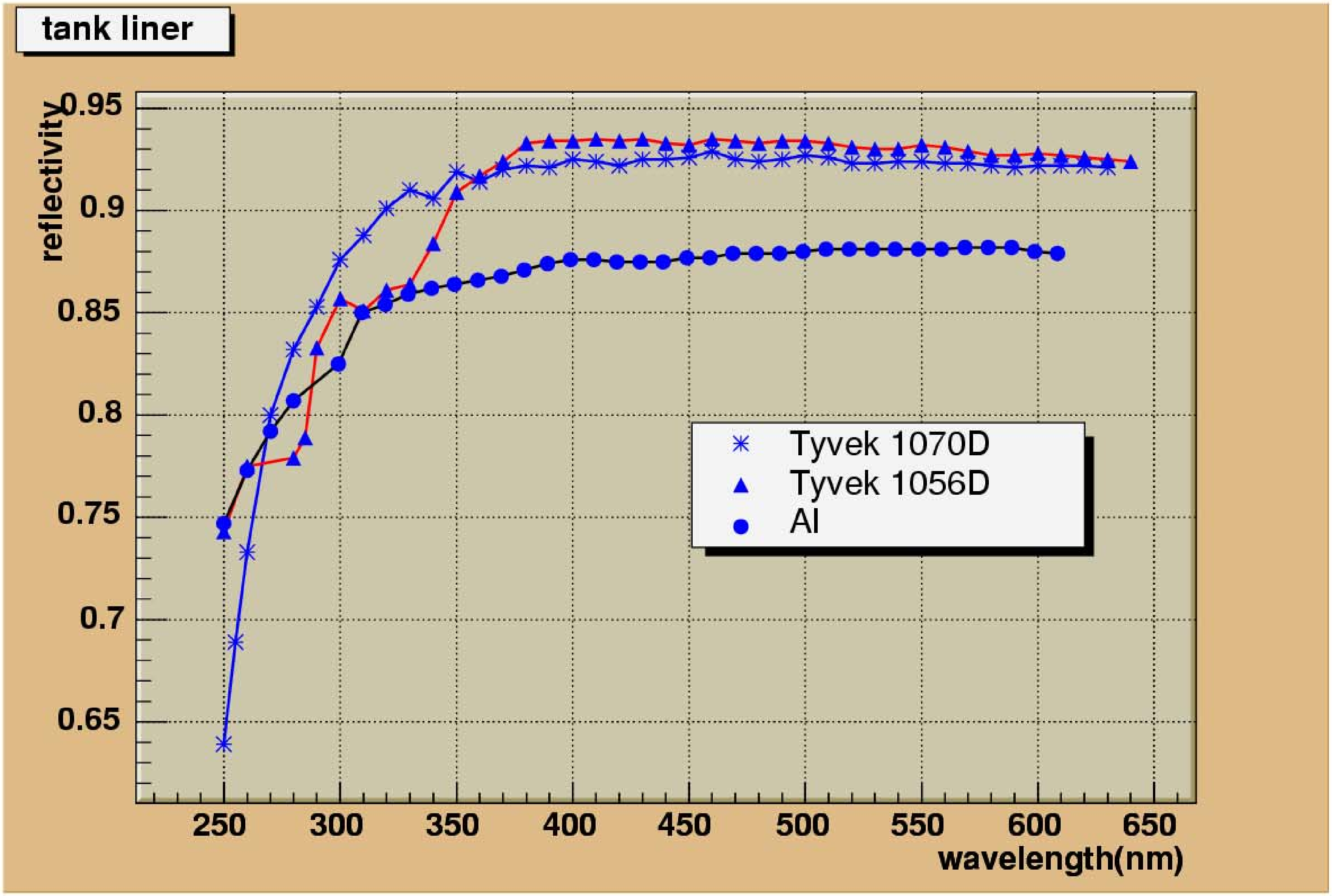
Sophisticated jet reconstruction algorithm, shower shape analysis and neural network should yield better results

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

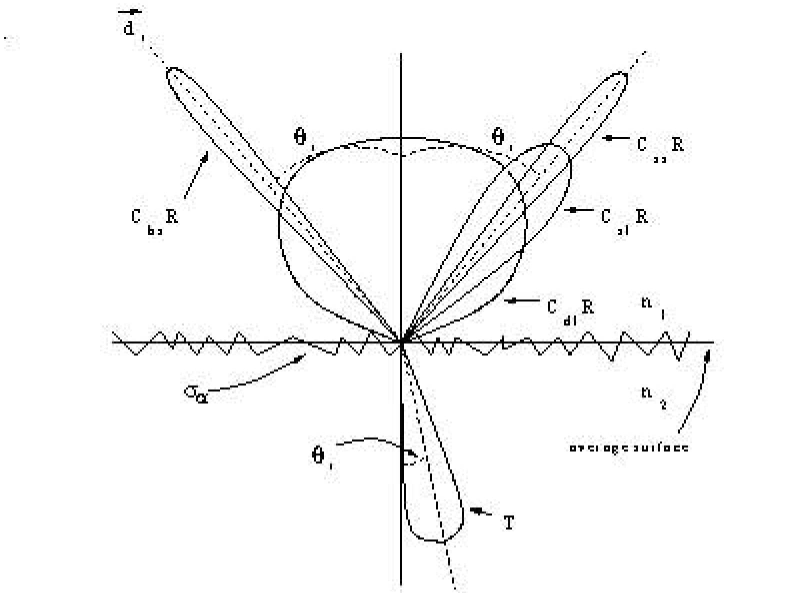


Statistical error only

Prototype: 0.3*0.3*3 m^3

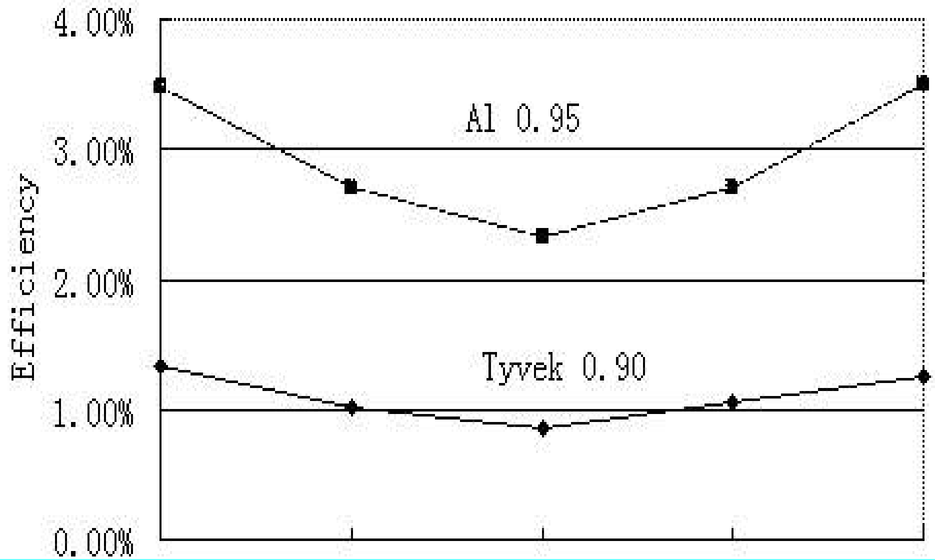


tank liner
reflectivity
0.95
0.9
0.85
0.8
0.75
0.7
0.65
250
300
350
400
450
500
550
600
650
wavelength(nm)
Tyvek 1070D
Tyvek 1056D
Al



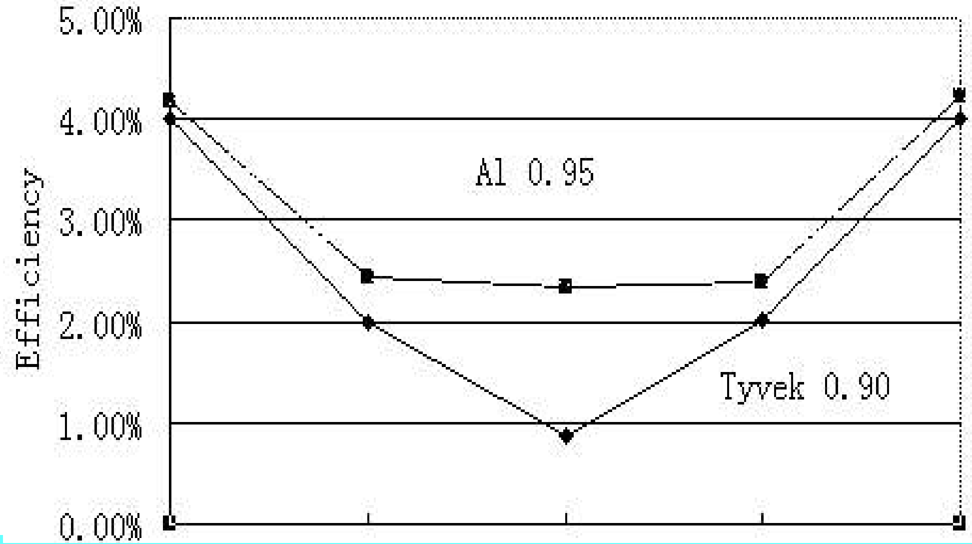
Unified Optical model In GEANT4

Simulation of the optical light collection



-4 -2 0 2 4 (m)

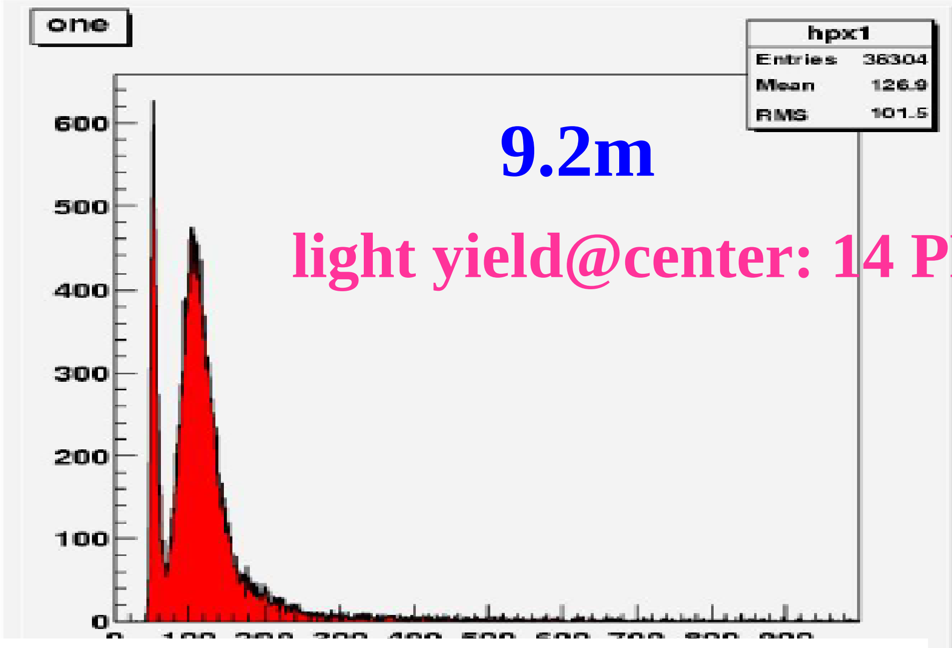
position



-60^0 -30^0 0^0 30^0 60^0

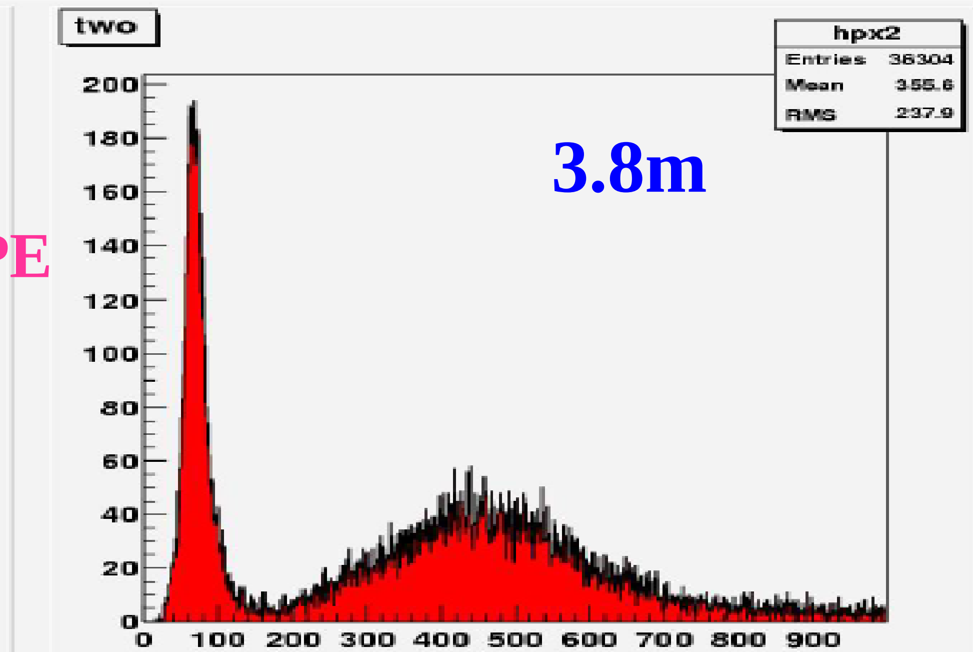
Incident angle

1*1*14 full size tank

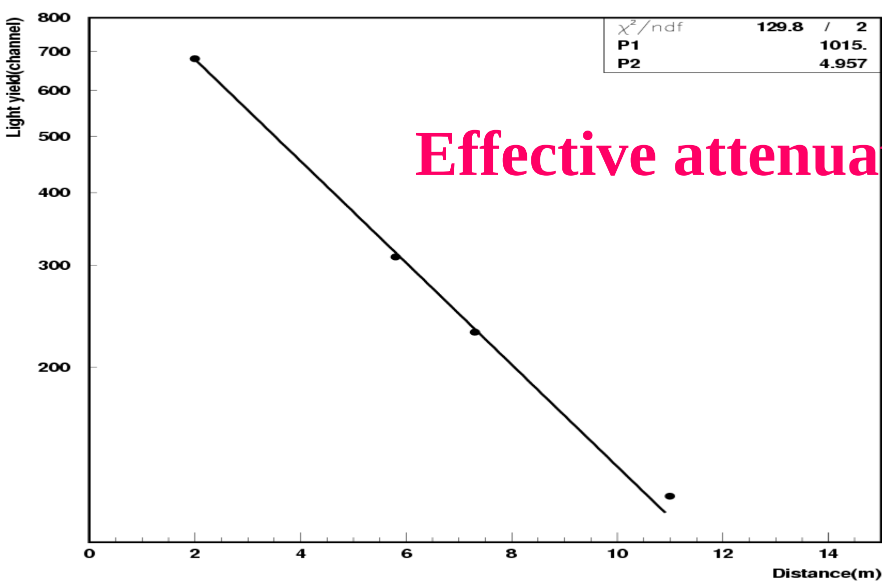


9.2m

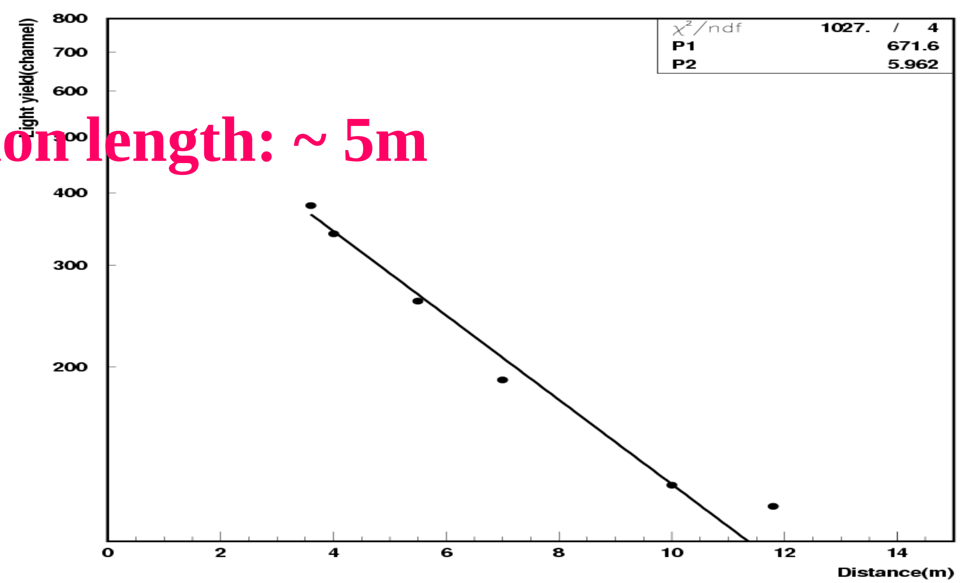
light yield@center: 14 PE



3.8m



Effective attenuation length: ~ 5m



Lab for LBL ? overburden: 150m

Total Volume: 250K m^3