Superbeam, Beta Beam, and Neutrino Factory (1)

Yoshitaka Kuno
Osaka University

61st Scottish Summer School in Physics
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Plan of My Lectures

- First Lecture (August 16th)
  - Fundamentals of Neutrino Oscillation
  - Superbeam Experiments
- Second Lecture (August 17th)
  - Neutrino Factory
  - Beta Beam Facility
- Third Lecture (August 18th)
  - Neutrino Factory (continued)

Outline (First Lecture)

- Brief Introduction of Neutrino Oscillation
- Neutrino Sources
- SuperBeams (in particular future projects, not current nor near-future)
  - Superbeams in Japan
  - Superbeams in the US
  - Superbeams in Europe
- Summary

Neutrinos Have Mass !!

- ...., although they are tiny,
- Are neutrinos are fundamentally different ?
- Are the neutrino mass generated by distinct mechanism ?
- first evidence of physics beyond the Standard Model ?
- Will future accelerator-based neutrino facilities be able to give some hints ?

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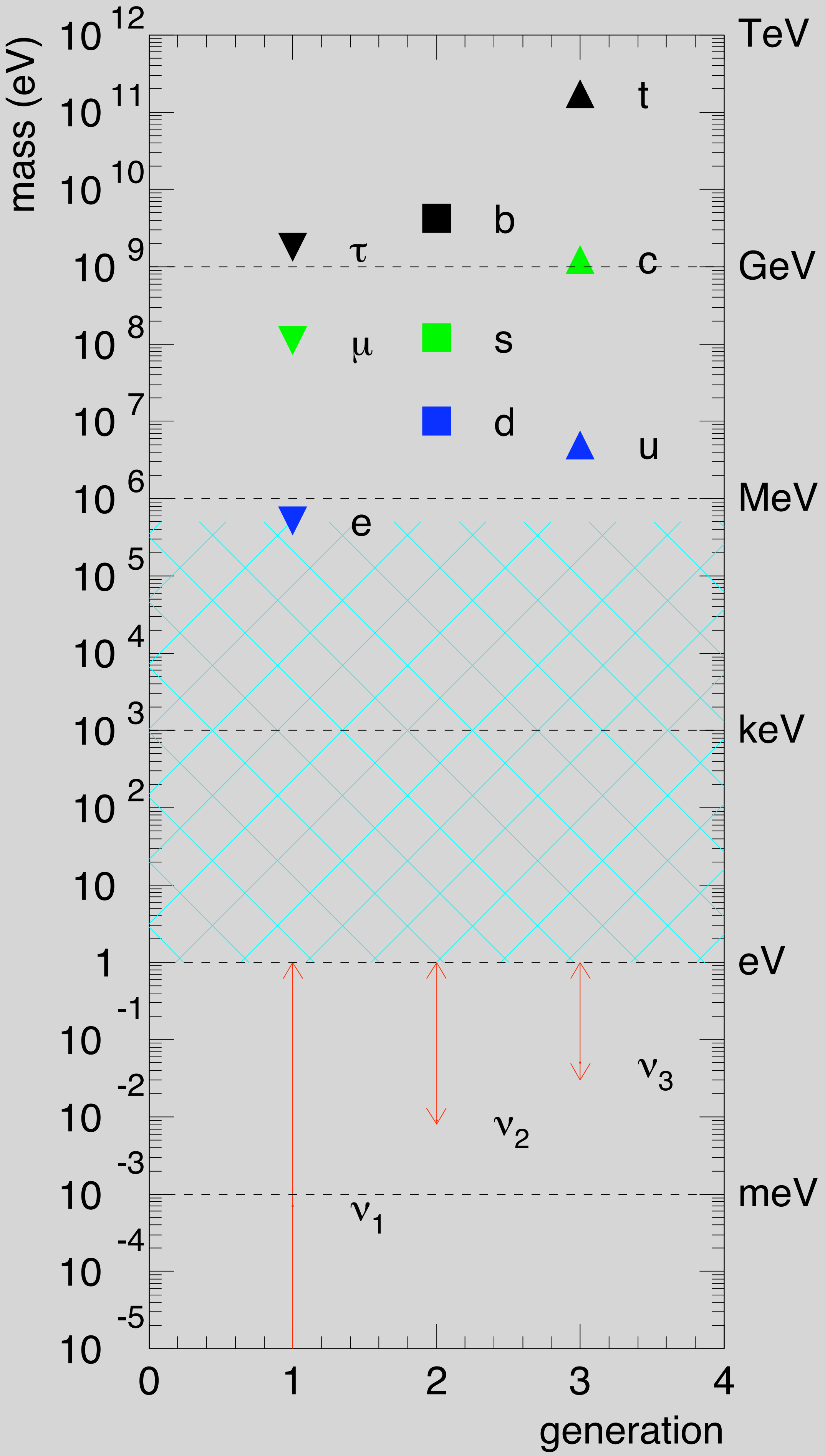

The Big Questions

- What is the origin of neutrino mass?
- Did neutrinos play a role in our existence?
- Did neutrinos play a role in forming galaxies?
- Did neutrinos play a role in birth of the universe?
- Are neutrinos telling us something about unification of matter and/or forces?
- Will neutrinos give us more surprises?

Big questions ≡ tough questions to answer

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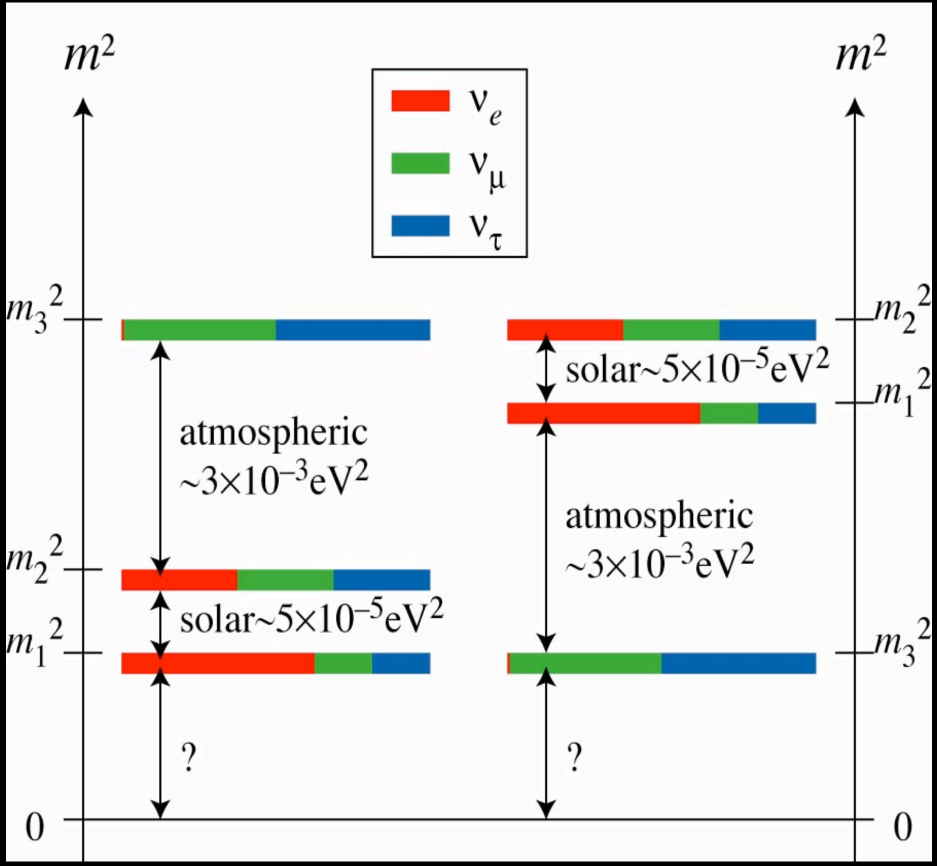
If huge money is spent for future neutrino facilities, it is desirable to address some of such big questions.

Immediate Questions

- Dirac or Majorana?
- Absolute mass scale?
- How small is θ_{13}?
- CP Violation?
- Mass hierarchy?
- Is θ_{23} maximal?



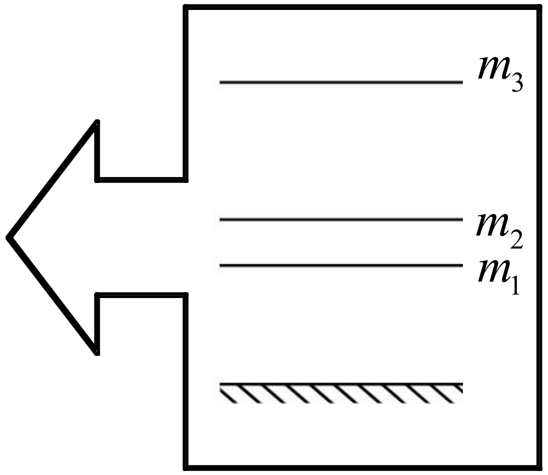
- LSND? Sterile neutrino(s)? CPT violation?

Three Generation Neutrino Mixing

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

Standard Model states

Neutrino mass states



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric angle

Reactor angle and CP phase

Solar angle

Majorana phases

Three Generation Neutrino Mixing

Maki-Nakagawa-Sakata (MNS) 3x3 Unitary Matrix 1962

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

$$\times \begin{pmatrix} e^{-i\frac{\phi_1}{2}} & 0 & 0 \\ 0 & e^{-i\frac{\phi_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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three mixing angle

$$\theta_{12} \quad \theta_{23} \quad \theta_{13}$$

three imaginary phase (Dirac or Majorana)

$$\delta \quad \phi_1 \quad \phi_2$$

mass squared difference

$$|\Delta m^2_{21}|, |\Delta m^2_{31}|, \mathrm{Sgn}(\Delta m^2_{31})$$

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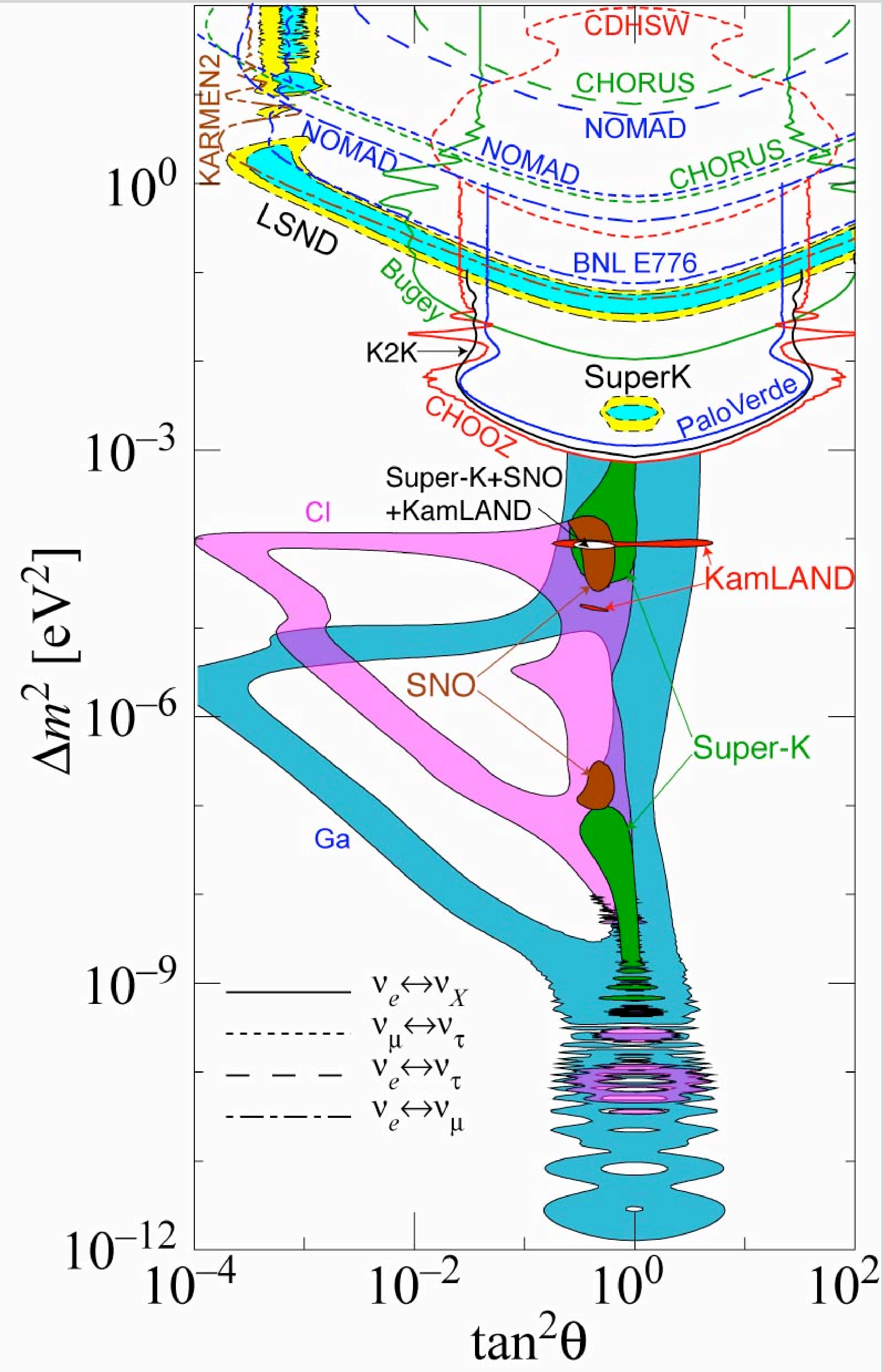
$\boxed{|\Delta m^2_{21}|, |\Delta m^2_{31}|}\boxed{\mathrm{Sgn}(\Delta m^2_{31})}$

to be determined in future
oscillation neutrino facilities

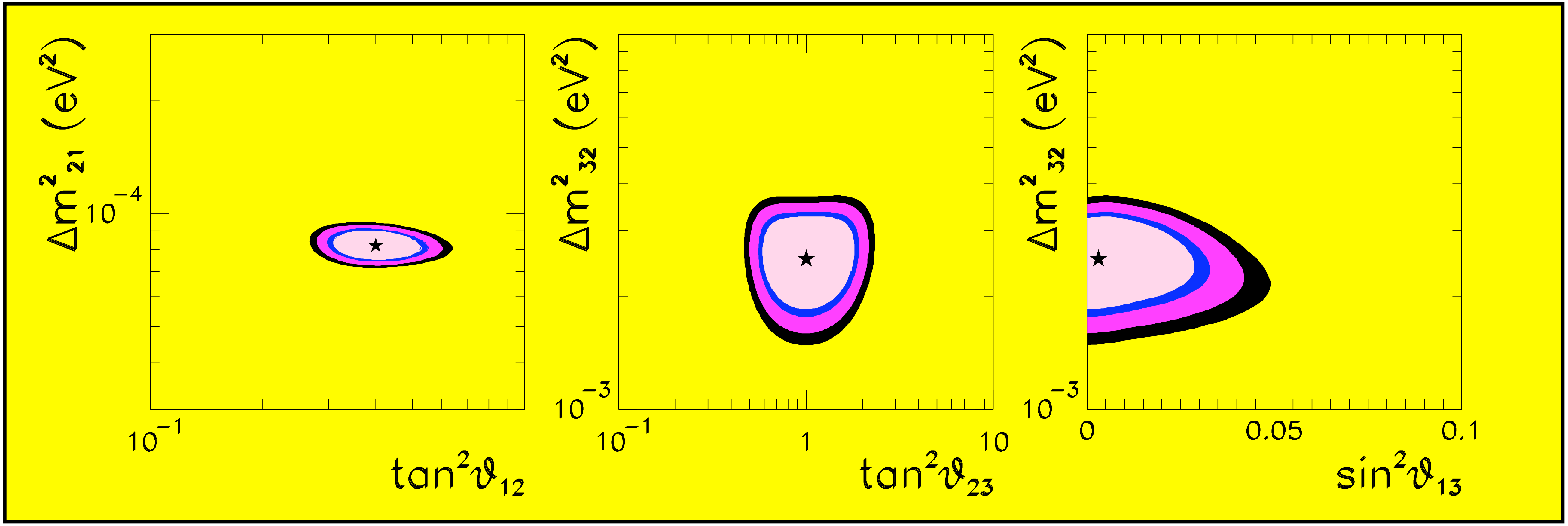
Neutrino Masses From Neutrino Oscillations

- Atmospheric Neutrinos
- Solar Neutrinos
- Reactor Neutrinos
- Accelerator Neutrinos



http://hitoshi.berkeley.edu/neutrino

The Knowns



solar atmospheric reactor

$$\Delta m^2_{31} = (2.2^{+1.1}_{-0.8}) \times 10^{-3} eV^2$$
$$\Delta m^2_{21} = (8.1^{+1.0}_{-0.9}) \times 10^{-5} eV^2$$

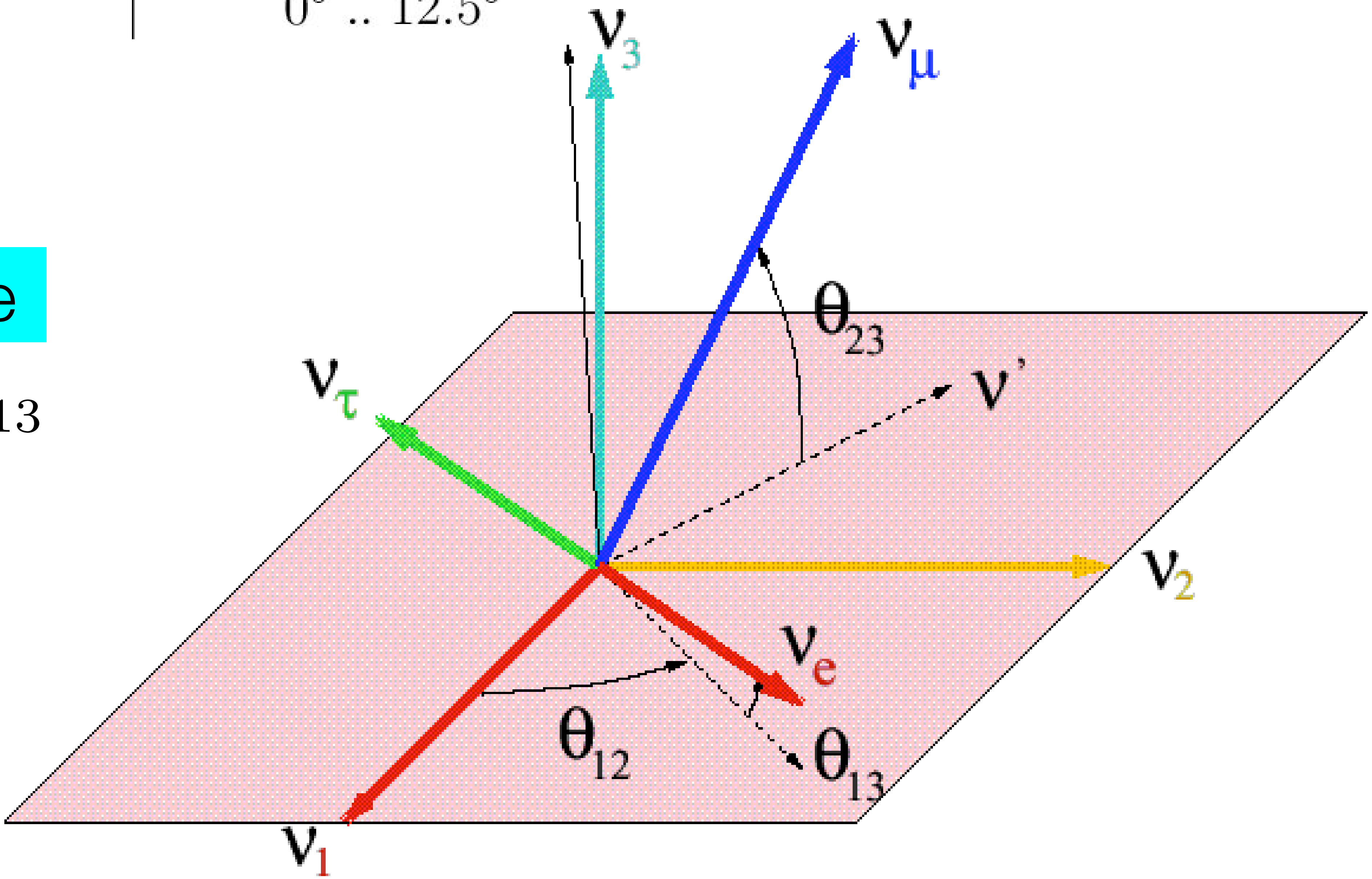
$$\sin^2\theta_{23} = 0.5^{+0.18}_{-0.16}$$
$$\sin^2\theta_{12} = 0.3^{+0.08}_{-0.07}$$
$$\sin^2\theta_{13} = 0^{+0.047}_{-0}$$

3 Lepton Mixing Angles

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

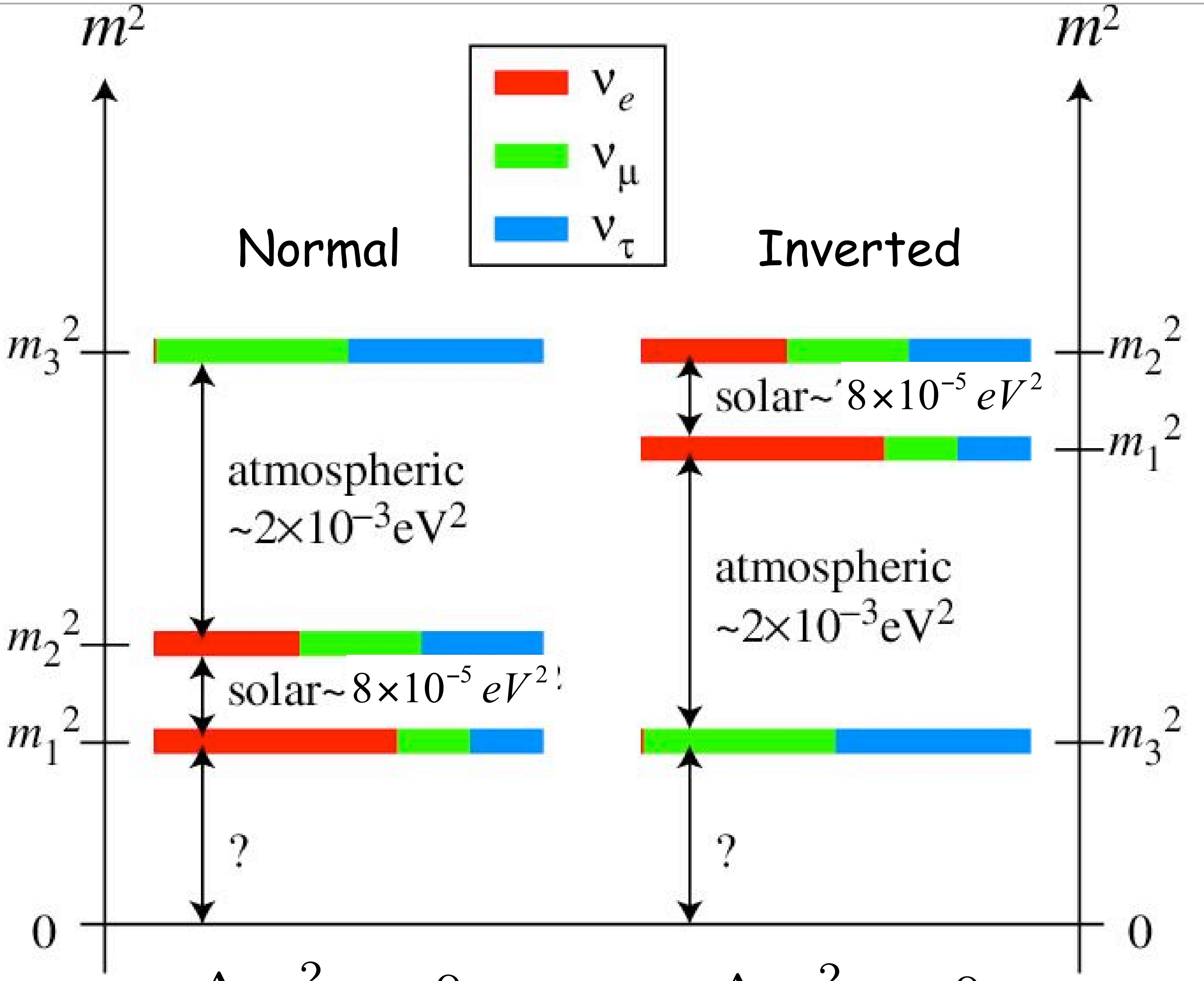
three mixing angle

θ_{12} θ_{23} θ_{13}



$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Neutrino Mass Spectrum (Mass Hierarchy)



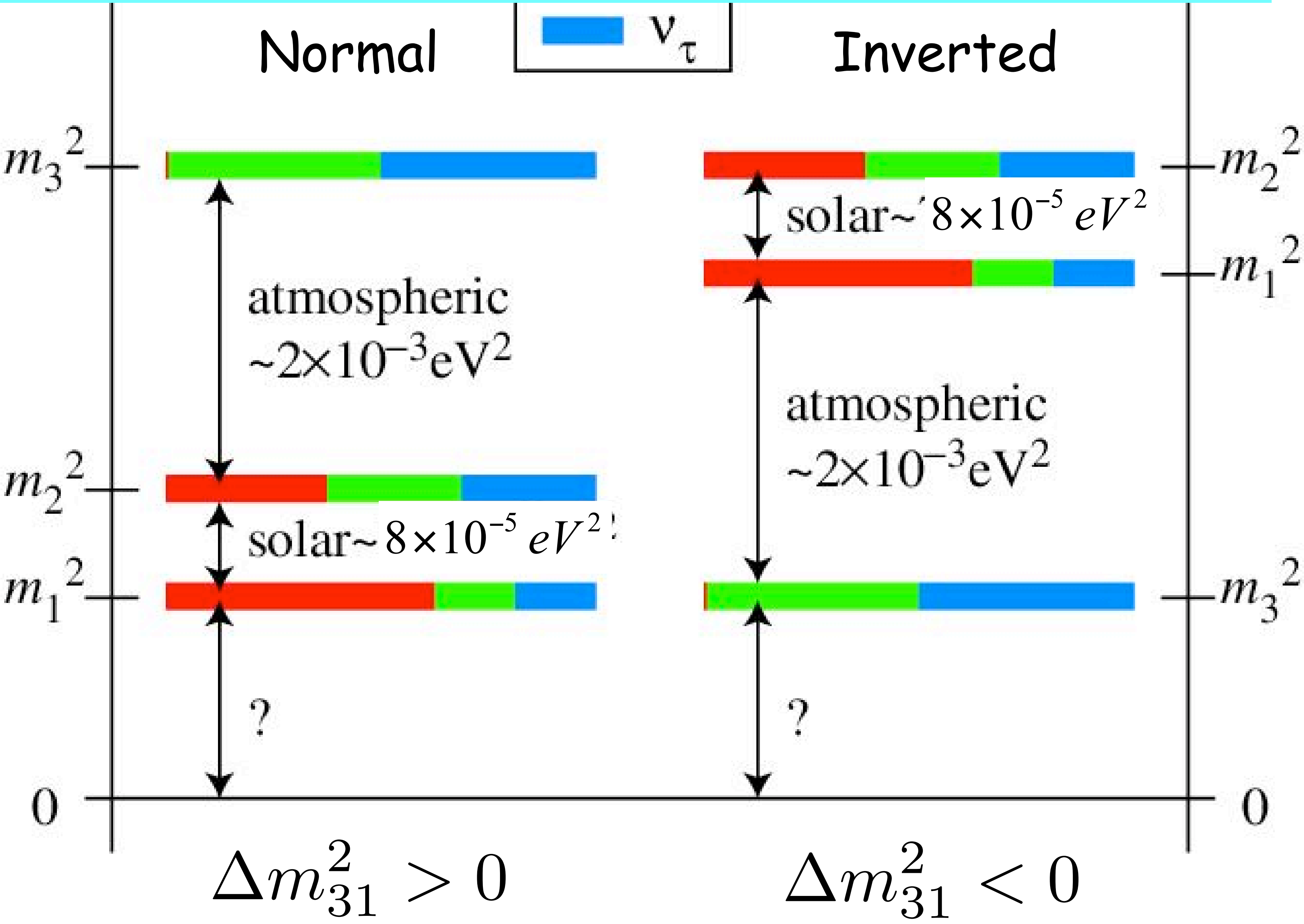
$\Delta m_{31}^2 > 0$

$\Delta m_{31}^2 < 0$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Neutrino Mass Spectrum (Mass Hierarchy)

Whether Normal or Inverted Hierarchy has to be determined !



Neutrino Oscillation Probability

$$P(\nu_l \to \nu_m) = \left| \sum_j V_{mj} V_{lj}^* exp(-i\frac{m_j^2 L}{2E}) \right|^2$$

2 flavor approximation:

$$P(\nu_l \to \nu_m) = \sin^2(2\theta)\sin^2(\frac{\Delta m^2 L}{4E})$$

$$P(\nu_l \to \nu_l) = 1 - \sin^2(2\theta)\sin^2(\frac{\Delta m^2 L}{4E})$$

In the past studies, 2 flavor approximation has been almost sufficient.

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☑ 2 neutrino flavor approximation is not sufficient.

3 neutrino flavor framework should be used.

☑ Vacuum oscillation approximation is not sufficient for long baseline experiments.

MSW parameter mapping in matter should be used.

Neutrino Oscillation Probabilities

- full numerical simulation
- $\Delta = \Delta m^2_{31} L/4E$
- qualitative understanding $\Rightarrow$ expand in $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin^2 2\theta_{13}$
- matter effects $\hat{A} = A/\Delta m^2_{31} = 2VE/\Delta m^2_{31};\ \ V = \sqrt{2} G_F n_e$

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \cos^2\theta_{13} \sin^2 2\theta_{23} \sin^2\Delta + 2\,\alpha\ \cos^2\theta_{13} \cos^2\theta_{12} \sin^2 2\theta_{23} \Delta \cos\Delta$$

$$\begin{aligned}
P(\nu_e \to \nu_\mu) \approx\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
\pm\ & \sin\delta_{\mathrm{CP}}\ \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+\ & \cos\delta_{\mathrm{CP}} \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+\ & \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}$$

Next Generation Oscillation Physics (Goals)

- Measure θ_{13} with high accuracy, or improve the limit of θ_{13} of a few orders of magnitude.
- If $\theta_{13} \neq 0$ is determined, measure the CP violating phase δ with good precision.
- Solve the neutrino mass hierarchy by measuring the sign of Δm^2_{32}
- Discriminate the maximal / non-maximal θ_{23}

$$\theta_{23}\ \left(\theta_{23} = \frac{\pi}{4},\ \text{or}\ \theta_{23} > \frac{\pi}{4},\ \text{or}\ \theta_{23} < \frac{\pi}{4}\right)$$

Disappearance Channels

$\nu_\mu \to \nu_\mu (\bar{\nu}_\mu \to \bar{\nu}_\mu)$ oscillation

$$P^{\pm}_{\nu_\mu \nu_\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{23} L}{4E}\right) + \mathcal{O}\left(\theta^2_{13} \sin^2 \left(\Delta m^2_{23} L/4E\right)\right)$$

$$+ \quad \mathcal{O}(\cos \delta_{CP} \cdot \theta_{13} \cdot \Delta_{12} \cdot \sin(\Delta m^2_{23} L/4E)) + \mathcal{O}(\Delta^2_{12})$$

Almost no information on

θ_{13} and δ

Good for precise measurements of

$\sin 2\theta_{23}$ and Δm^2_{23}

CP Violation

CP Asymmetry

$$A_{CP} = \frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)}$$

$$P_{CP-odd}(\nu_e \to \nu_\mu) \approx -4J\frac{\delta m_{21}^2 L}{2E_\nu}\sin^2\left(\frac{\delta m_{31}^2 L}{4E_\nu}\right)$$

$$\text{Jarlskog parameter}\ :J = c_{12}c_{13}^2c_{23}s_{12}s_{13}s_{23}\sin(\delta)$$

$$\begin{aligned} A_{CP} &= \frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)} \\ &\approx \underline{\sin\delta}\cdot\left(\frac{\Delta m_{12}^2 L}{E}\right)\frac{\sin 2\theta_{12}}{\sin\theta_{13}} \end{aligned}$$

CP Asymmetry Figure of Merit

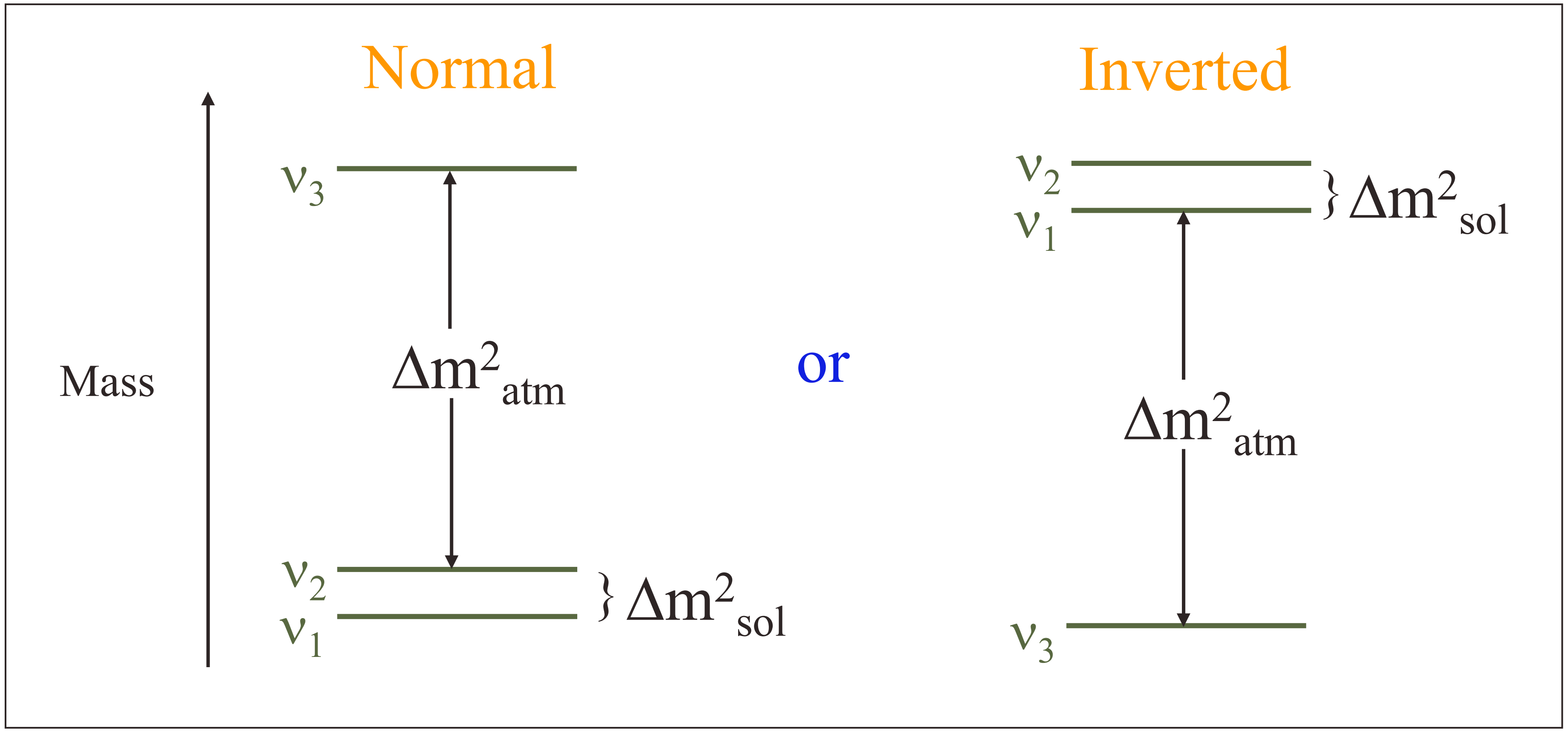
$$A_{CP-odd} \equiv \frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e - \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e - \bar{\nu}_\mu)} \propto \frac{L}{E_\nu}$$

$$N_{osc} \propto \left(\frac{E_\nu}{L}\right)^2 \sin^2\left(\frac{\delta m_{31}^2 L}{4E_\nu}\right)\sigma(E_\nu) \propto E_\nu$$

$$FOM \equiv A_{CP-odd}^2 \times N_{osc} \propto \left(\frac{L}{E_\nu}\right)^2 E_\nu$$

○for fixed L, low energy is better.
○for the same L/E, higher E is better.
○Matter effect is also large for large L.

Determination of Sign of the Mass Hierarchy



Normal

Inverted

Mass

or

ν_3

$\Delta m^2_{\mathrm{atm}}$

ν_2

ν_1

$\}\ \Delta m^2_{\mathrm{sol}}$

ν_2

ν_1

$\}\ \Delta m^2_{\mathrm{sol}}$

$\Delta m^2_{\mathrm{atm}}$

ν_3

$\Delta m^2_{\mathrm{sol}} \cong 8 \times 10^{-5}\ \mathrm{eV}^2$, $|\Delta m^2_{\mathrm{atm}}| \cong 2.5 \times 10^{-3}\ \mathrm{eV}^2$

From the matter effect,

$$\text{if } \Delta m^2_{32} > 0,\ P(\nu_e \to \nu_\mu) \text{ increases.}$$
$$\text{if } \Delta m^2_{32} < 0,\ P(\bar{\nu}_e \to \bar{\nu}_\mu) \text{ increases.}$$

A longer baseline will be needed to determine the mass hierarchy.

Appearance Channels

$\nu_e \longrightarrow \nu_\mu(\bar{\nu}_e \longrightarrow \bar{\nu}_\mu)$ oscillation

+ for neutrino, - for antineutrino

$$P^{\pm}_{\nu_e\nu_\mu}(\theta_{13},\delta) \approx X_\pm \sin^2 2\,\theta_{13} + \left(Y^c_\pm \cos\delta \mp Y^s_\pm \sin\delta\right)\sin 2\,\theta_{13} + Z$$

with $X_\pm, Y^c_\pm, Y^s_\pm$ and Z functions of the known parameters:

$$\left\{\begin{aligned}
X_\pm &= \boxed{\sin^2\theta_{23}}\left(\frac{\Delta_{23}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right) \\
Y^c_\pm &= \boxed{\sin 2\theta_{23}}\sin 2\theta_{12}\,\frac{\Delta_{12}}{A}\,\frac{\Delta_{23}}{\tilde{B}_\mp}\sin\left(\frac{A\,L}{2}\right)\sin\left(\frac{\tilde{B}_\mp\;L}{2}\right)\boxed{\cos\left(\frac{\Delta_{23}L}{2}\right)} \\
Y^s_\pm &= \boxed{\sin 2\theta_{23}}\sin 2\theta_{12}\,\frac{\Delta_{12}}{A}\,\frac{\Delta_{23}}{\tilde{B}_\mp}\sin\left(\frac{A\,L}{2}\right)\sin\left(\frac{\tilde{B}_\mp\;L}{2}\right)\boxed{\sin\left(\frac{\Delta_{23}L}{2}\right)} \\
Z &= \boxed{\cos^2\theta_{23}}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\left(\frac{AL}{2}\right)
\end{aligned}\right.$$

where $\Delta_{ij} = \Delta m^2_{ij}/2E$, $B_\mp = |A \mp \Delta_{23}|$ and A is the matter parameter.

Appearance Oscillation Channels

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with $X_\pm, Y^c_\pm, Y^s_\pm$ and Z functions of the known parameters:

$X_\pm$

$Y^c_\pm$

$Y^s_\pm$

Z

Strong Correlation between

θ_{13} and δ

more on degeneracies later

where $\Delta_{ij} = \Delta m^2_{ij}/2E$, $B_\mp = |A \mp \Delta_{23}|$ and A is the matter parameter.

Exercise 1

- Show that the L/E dependence of the 2 flavor Oscillation probability is given by

$$\sin^2(\frac{\Delta m^2 L}{4E}) = \sin^2(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})})$$

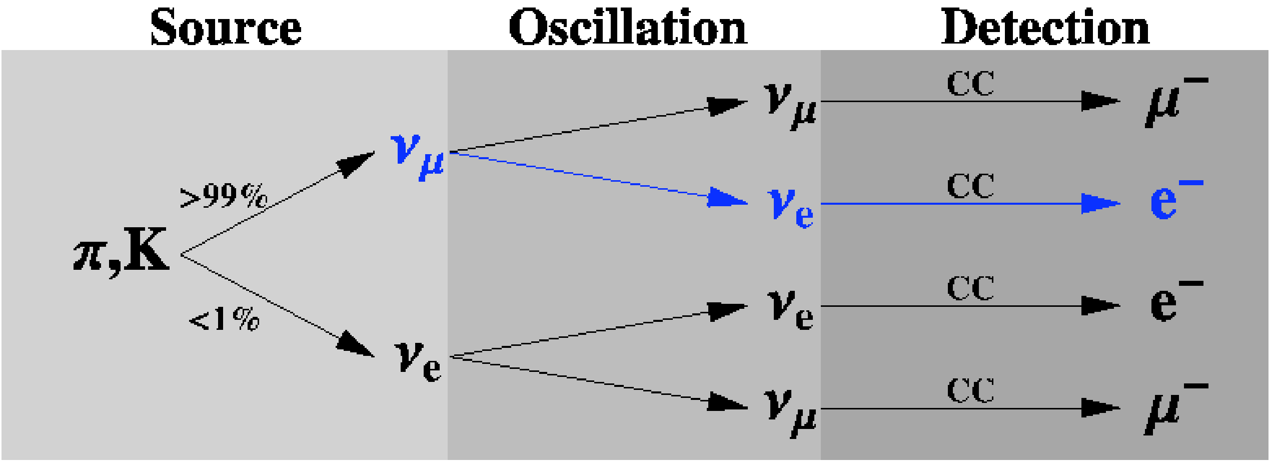
  - hints : the left-hand side of the above equation is presented in the natural unit. Use $\hbar c = 197\mathrm{MeV fm}$ to get the units back.

Neutrino Sources

Neutrino Sources

Neutrino Sources

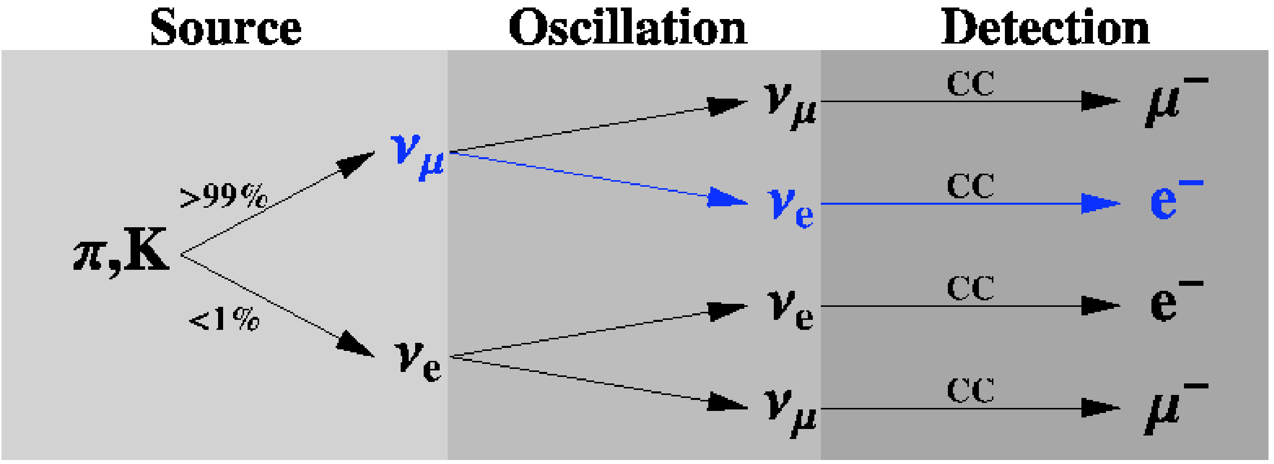
Pion Decays $\pi^+ \to \mu^+ \nu_\mu, \pi^- \to \mu^- \bar{\nu}_\mu$ Superbeam



$\nu_\mu \to \nu_e$ oscillation most interesting
ν_e contamination ⇔ off-axis
good electron detection efficiency
good NC background rejection
near detector
$\bar{\nu}$-beam $\simeq$ different experiment

Neutrino Sources

Pion Decays $\pi^+ \to \mu^+ \nu_\mu, \pi^- \to \mu^- \bar{\nu}_\mu$ Superbeam



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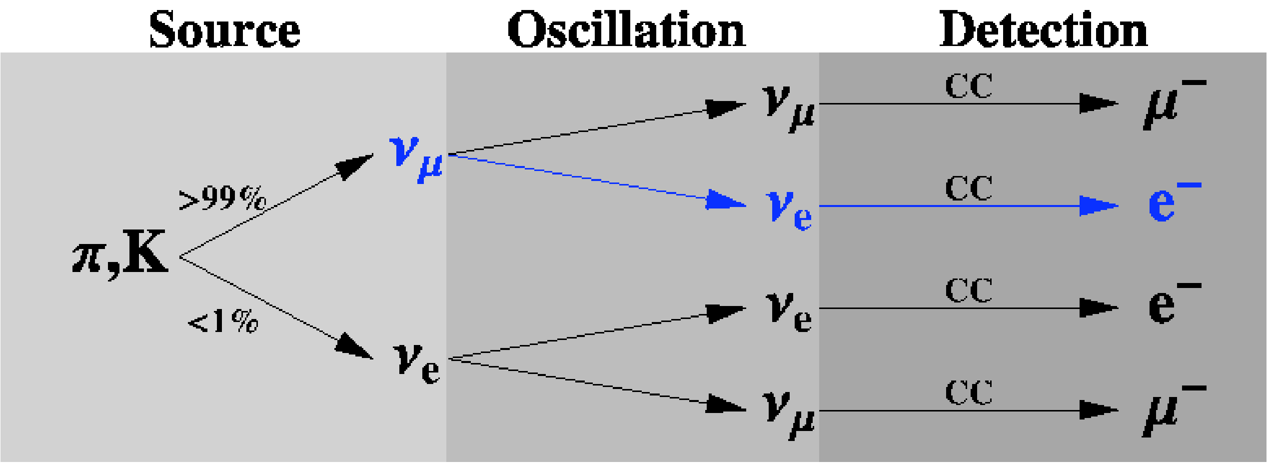
Beta Decays ${}^Z_A X \to {}^{Z-1}_A Y e^+ \nu_e, \; {}^Z_A X \to {}^{Z+1}_A Z e^- \bar{\nu}_e$

Beta Beam

Neutrino Sources

Pion Decays $\pi^+ \to \mu^+\nu_\mu, \pi^- \to \mu^-\bar{\nu}_\mu$ **Superbeam**



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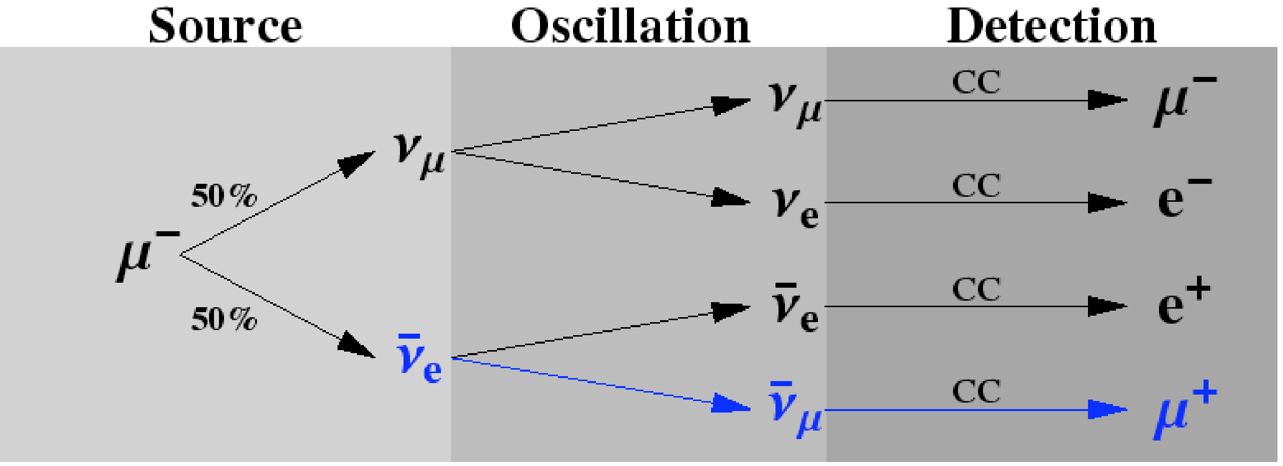
near detector

$\bar{\nu}$-beam $\simeq$ different experiment

Beta Decays $^{Z}_{A}X \to \ ^{Z-1}_{A}Ye^+\nu_e, \ ^{Z}_{A}X \to \ ^{Z+1}_{A}Ze^-\bar{\nu}_e$

Beta Beam

Muon Decays $\mu^+ \to e^+\nu_e\bar{\nu}_\mu, \mu^- \to e^-\bar{\nu}_e\nu_\mu$ **Neutrino Factory**



$\bar{\nu}_e \to \bar{\nu}_\mu$ oscillation most interesting

excellent beam properties

very good charge ID required

good NC background rejection

μ^+ mode very symmetric

Superbeams

What Is a Superbeam ?

- The “Superbeam” refers to future (anti) muon-neutrino beam facilities, based on pion-decays in conjunction with
  - higher proton intensity (~M Watt beam power) and
  - large neutrino detector(s).

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$
$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$

- Limitations :
  - difficult to achieve electron-neutrino contamination less than 0.5%
    - mostly from muon decays (and kaon decays)
- Advantages :
  - technology and problems well understood.
  - wide-band beam (on beam axis) and narrow-band beam (off beam axis) can be built.

List of Current and Superbeam Experiments

- Current Generation Experiments
  - K2K (at KEK) — confirm atmospheric oscillation
  - MINOS (at Fermilab) — measure $\sin^2 2\theta_{23}, \Delta m^2_{23}$ ~10%
  - MiniBooNE (at Fermilab) — confirm/refute LSND signal
  - OPERA/ICARUS (at CERN) — measure $\nu_\mu \rightarrow \nu_\tau$
- Next Generation Experiments
  - T2K (at J-PARC)
  - NOvA (at Fermilab)
- Future Generation Experiments
  - T2HK / T2KK (at J-PARC)
  - NOvA upgraded (at Fermilab)
  - CERN SPL-Frejus (at CERN)

- find out non-zero θ_{13} from oscillation of $\nu_\mu \rightarrow \nu_e$
- determine mass hierarchy
- more precisely measure $\sin^2 2\theta_{23}, \Delta m^2_{23}$
- search for CP violation if $\sin^2 2\theta_{13}$ is large.

$\sin^2 2\theta_{13} > 0.01$

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  - MINOS (at Fermilab) — measure $\sin^2 2\theta_{23}, \Delta m^2_{23}$ ~10%
  - MiniBooNE (at Fermilab) — confirm/refute LSND signal
  - OPERA/ICARUS (at CERN) — measure $\nu_\mu \to \nu_\tau$
- Next Generation Experiments
  - T2K (at J-PARC)
  - NOvA (at Fermilab)
- Future Generation Experiments
  - T2HK / T2KK (at J-PARC)
  - NOvA upgraded (at Fermilab)
  - CERN SPL-Frejus (at CERN)

- find out non-zero θ_{13} from oscillation of $\nu_\mu \to \nu_e$
- determine mass hierarchy
- more precisely measure $\sin^2 2\theta_{23}, \Delta m^2_{23}$
- search for CP violation if $\sin^2 2\theta_{13}$ is large.

$\sin^2 2\theta_{13} > 0.01$

Superbeam in Japan

T2K
T2HK (T2K Phase-II)
T2KK

T2K

- After K2K
- T2K = a long baseline neutrino beam experiment from Tokai to Kamioka
- Neutrino Source (Tokai)
  - J-PARC (Japan Proton Accelerator Research Complex)
  - 0.75 MW 40(50) GeV protons
- Neutrino Detector (Kamioka)
  - SuperKamiokande
    - 22.5 kton fiducial volume
- 295 km baseline
- about 1 GeV neutrino beam energy

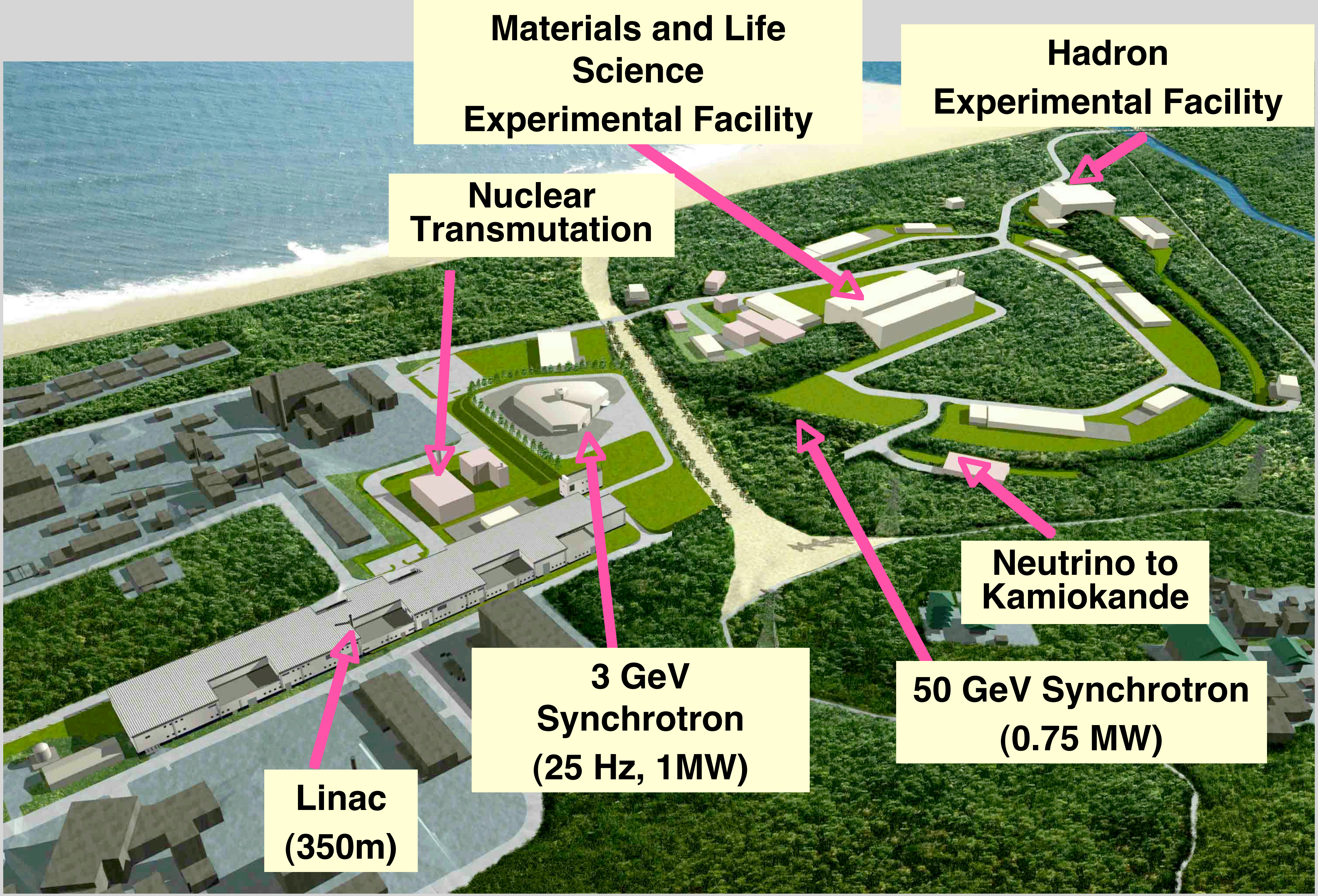
goal :

(1) measure appearance of

$$\nu_\mu \to \nu_e$$

(2) measure disappearance of

$$\nu_\mu \to \nu_\mu$$



Materials and Life Science Experimental Facility

Hadron Experimental Facility

Nuclear Transmutation

Neutrino to Kamiokande

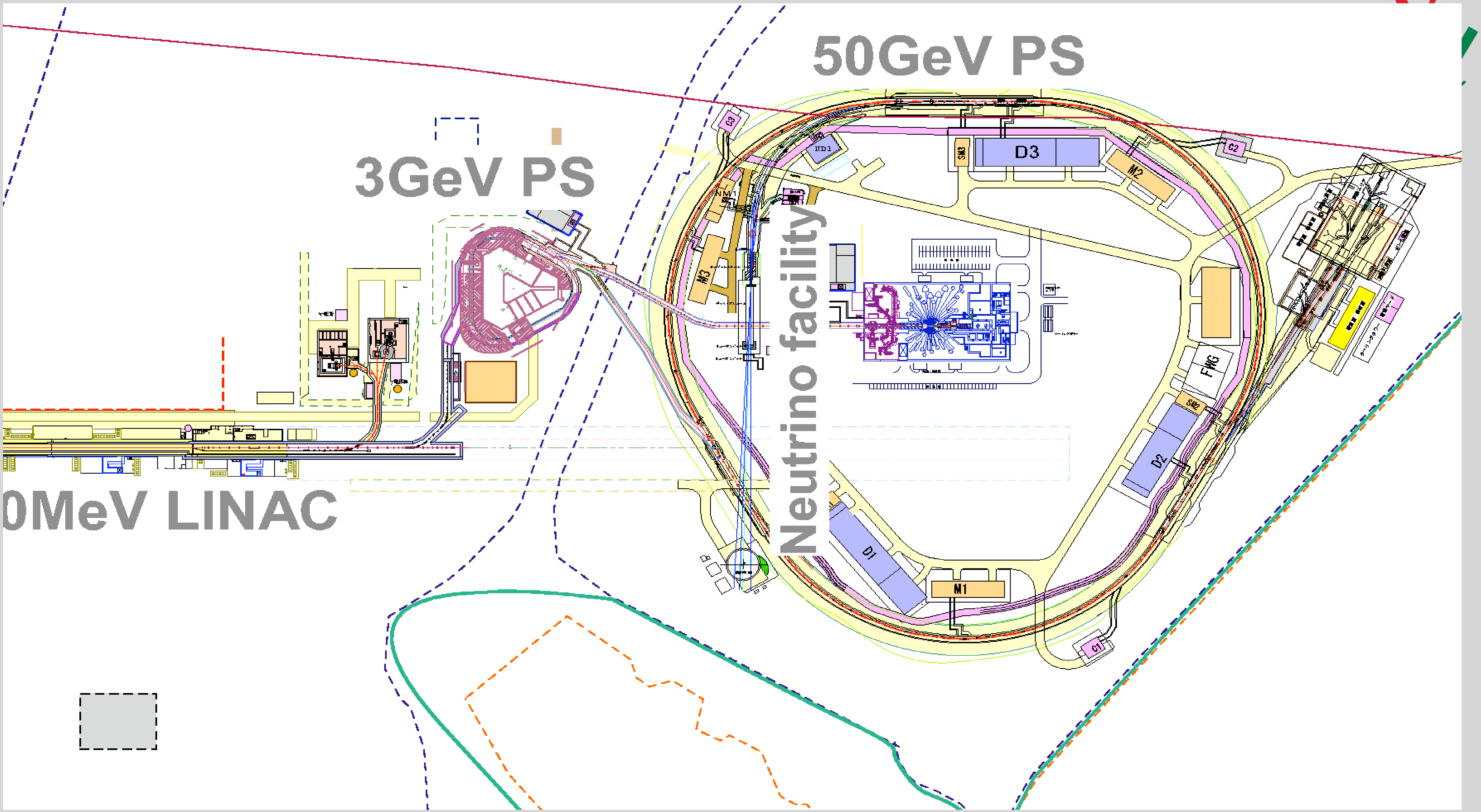
3 GeV Synchrotron (25 Hz, 1MW)

50 GeV Synchrotron (0.75 MW)

Linac (350m)

J-PARC

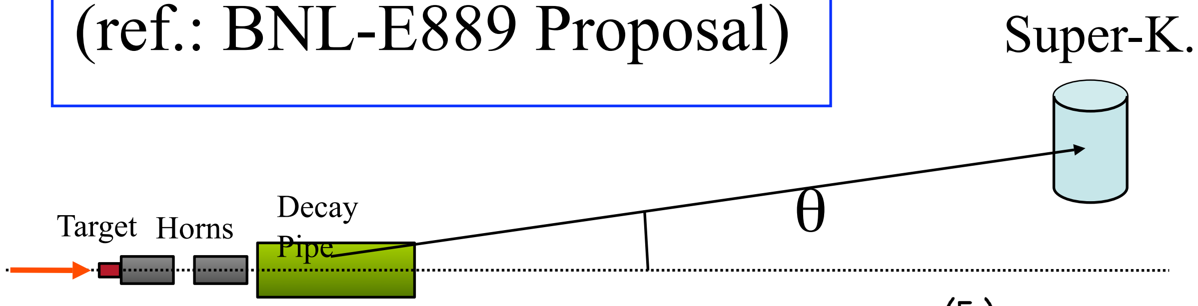
Japan Proton Accelerator Research Complex



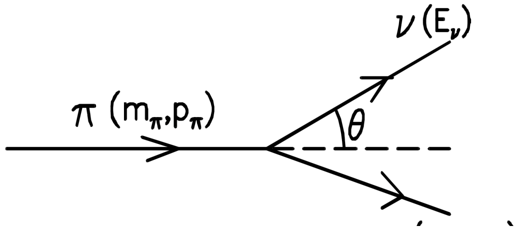
Neutrino Beam Line at J-PARC

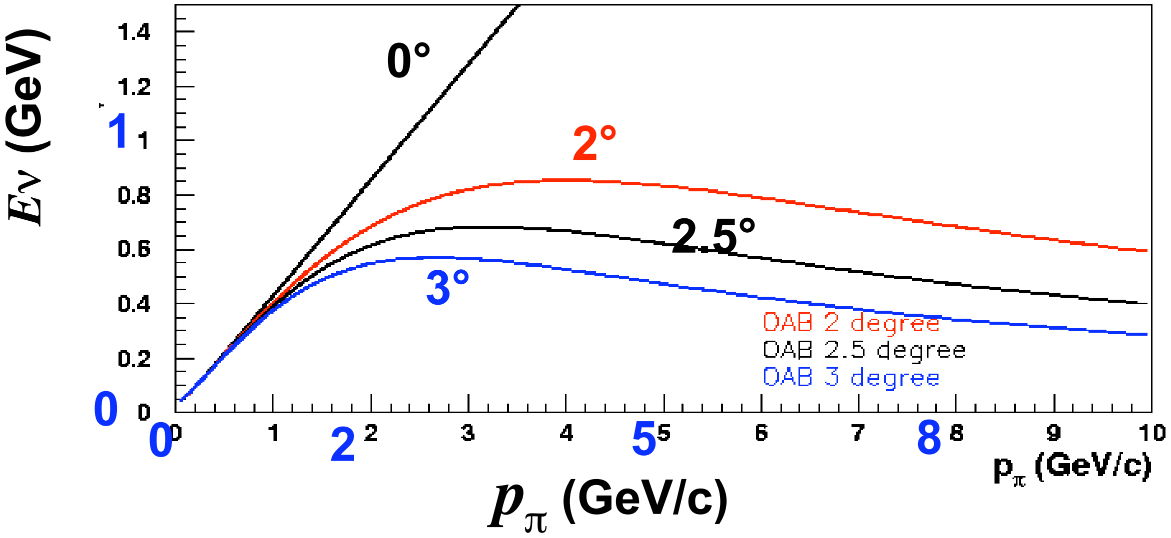
T2K Beam

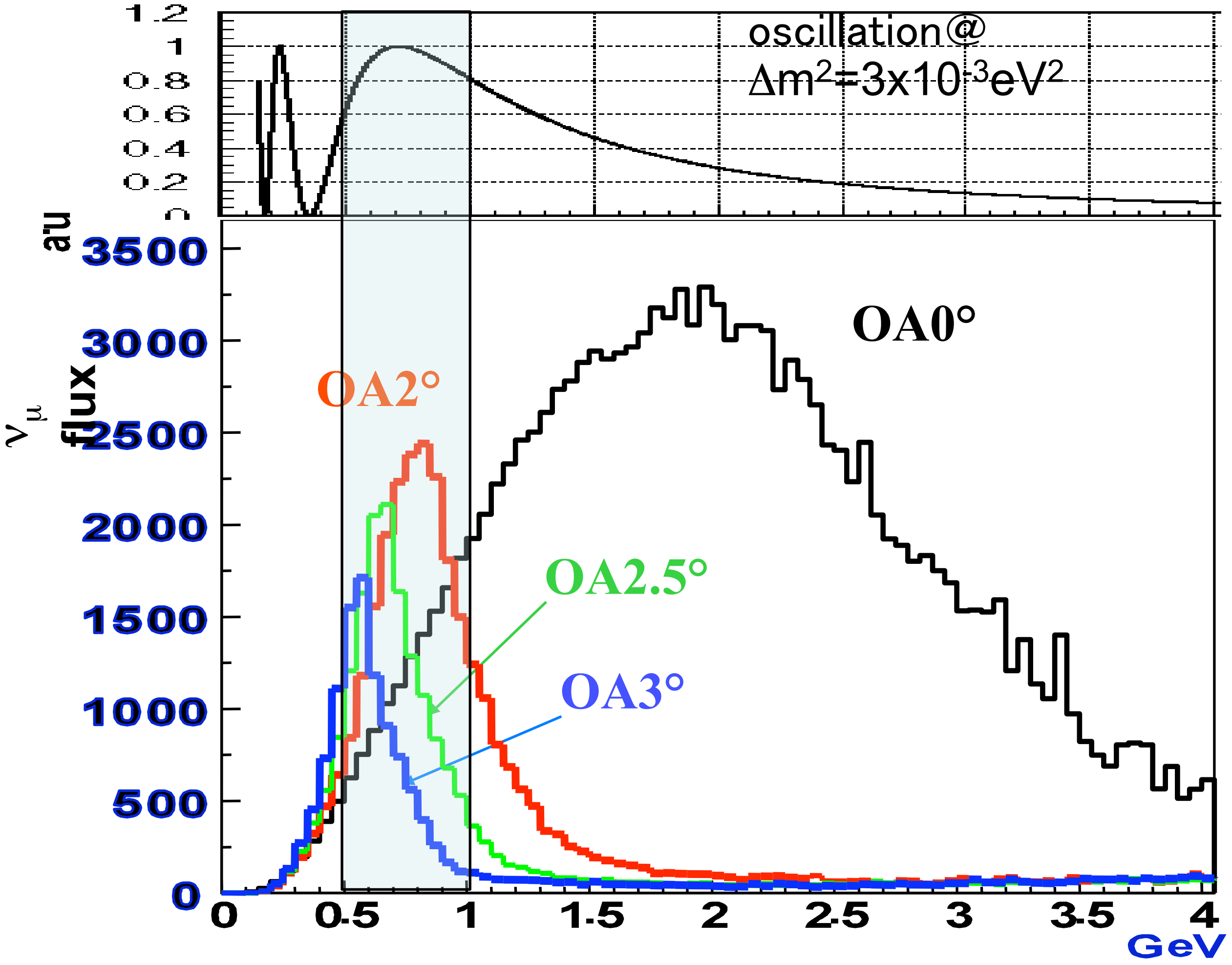
First Application
(ref.: BNL-E889 Proposal)



π decay Kinematics



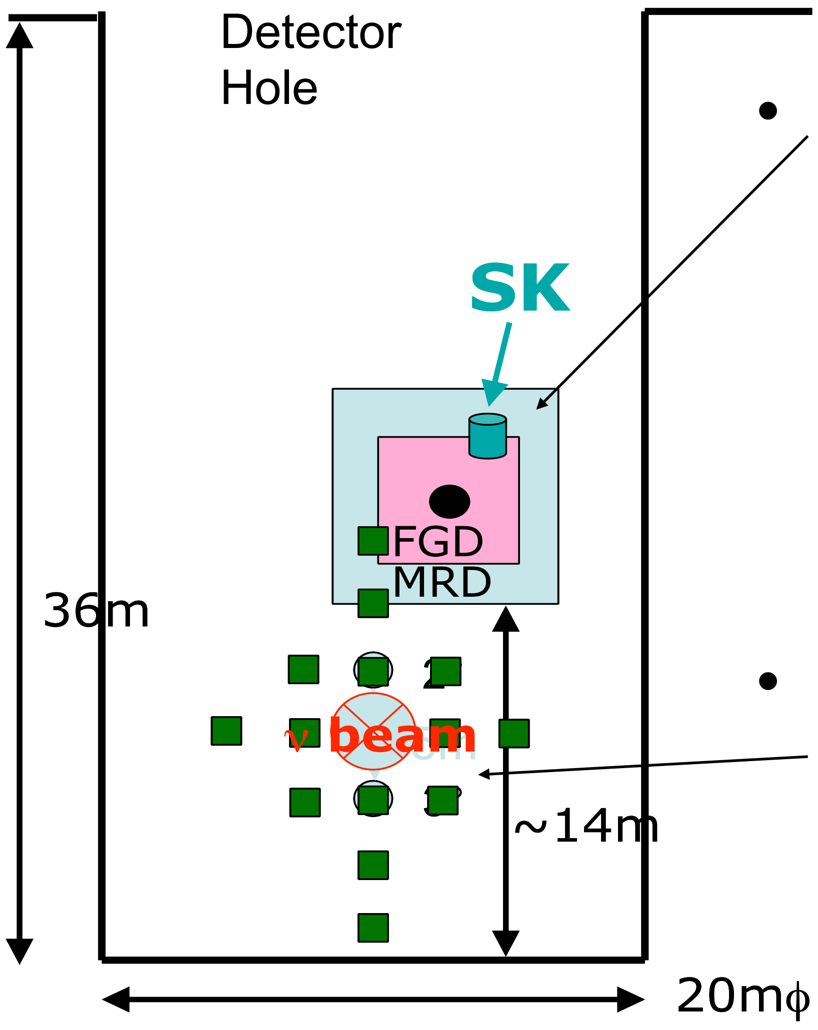




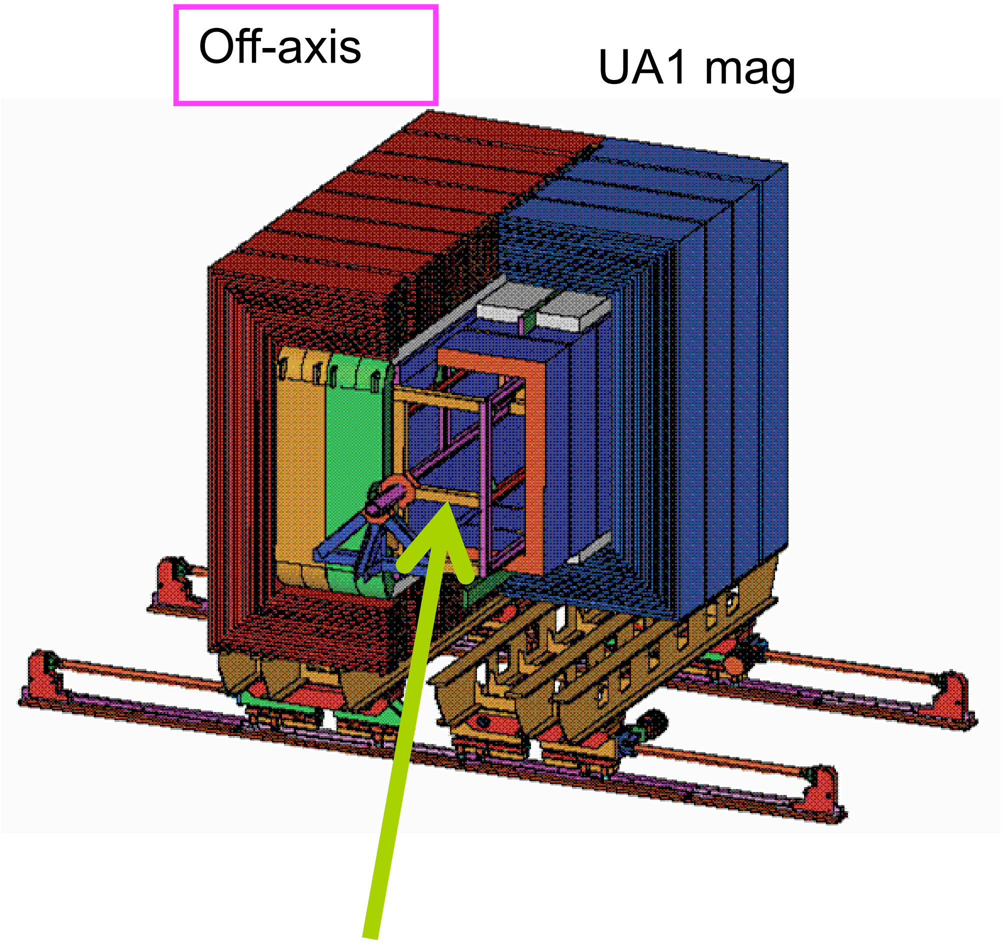
- **Quasi Monochromatic Beam**
- **x 2~3 intense than NBB**
- **Tuned at oscillation maximum**

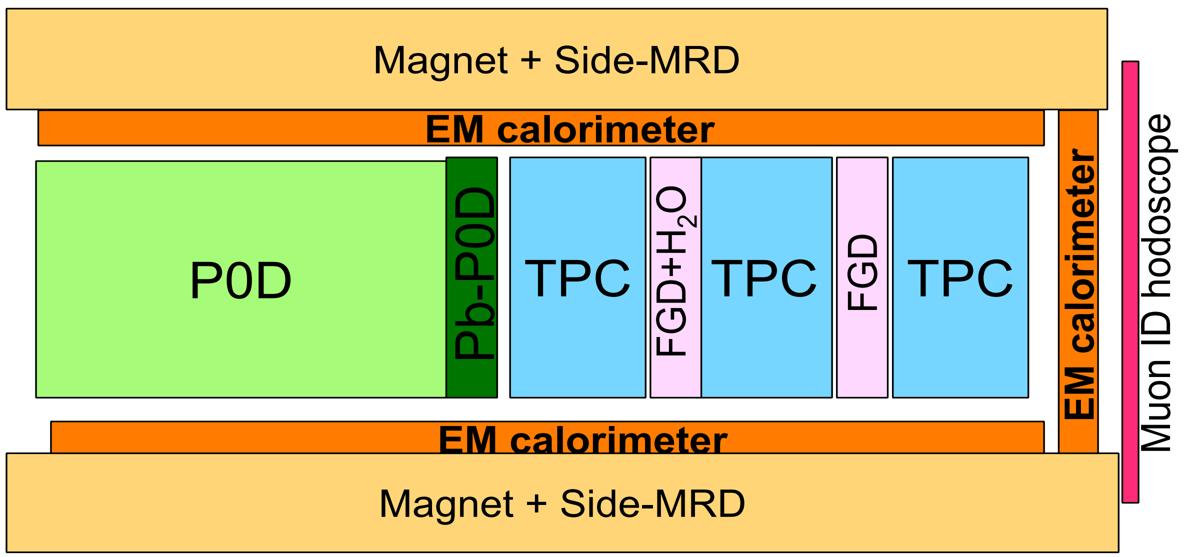
Statistics at SK
(OAB 2.5 deg, 1 yr, 22.5 ktons)
~ 2200 ν_μ tot
~ 1600 ν_μ CC

T2K Near Detector (Design)

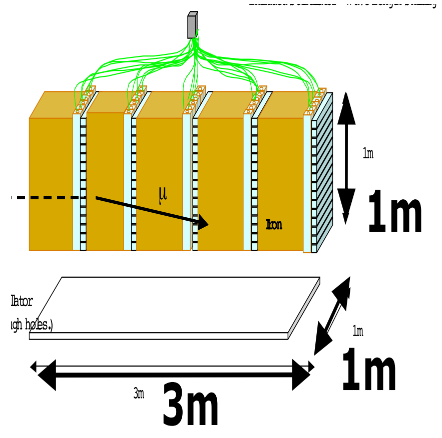


- Off-axis detector
  - ν spectrum
  - Cross sect.
  - ν_e contaminations.
  - UA1 mag, FGD, TPC, Ecal,..
- On axis detector
  - Monitor beam dir.
  - Grid layout

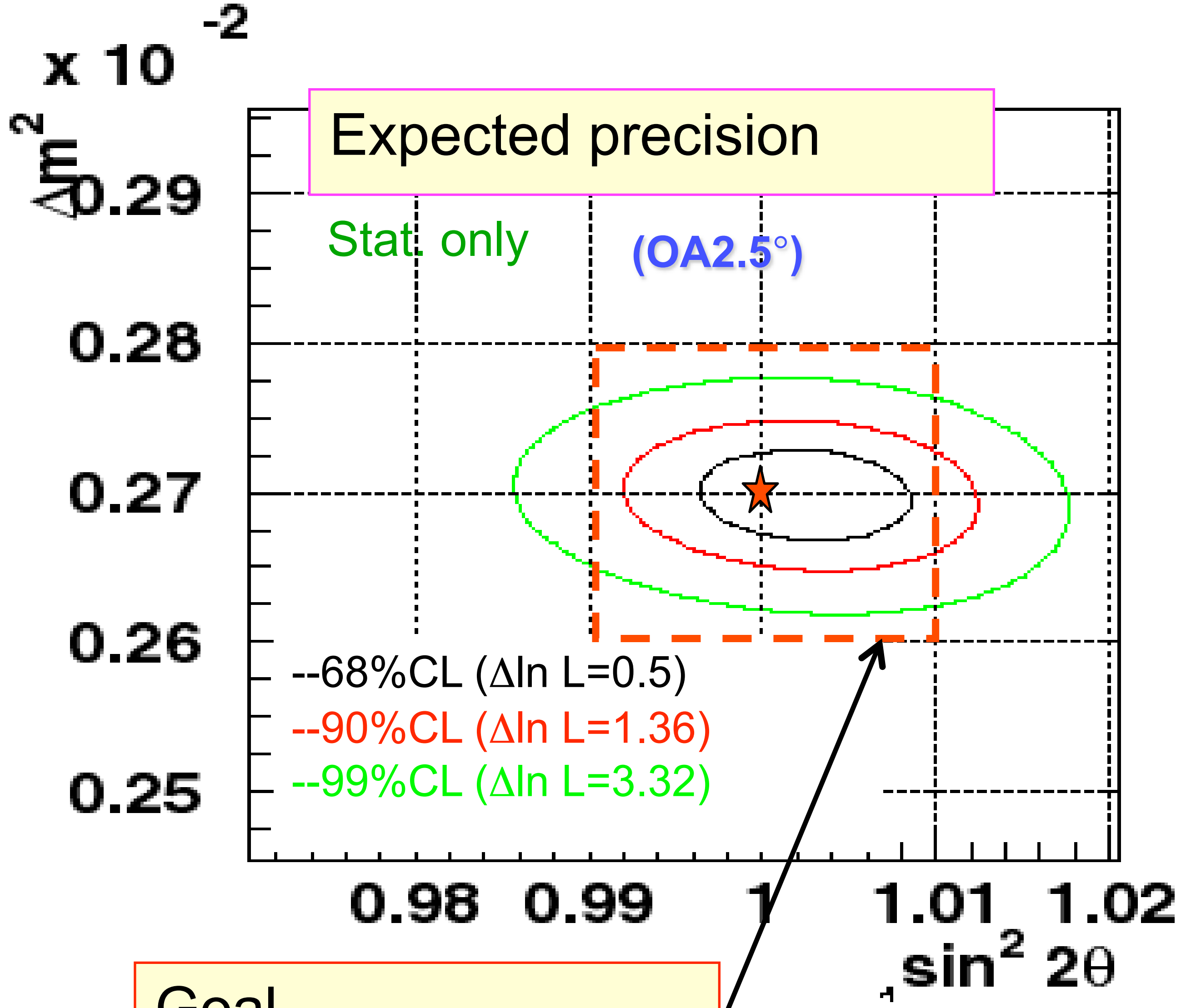




On-axis



T2K Sensitivity (disappearance channel)

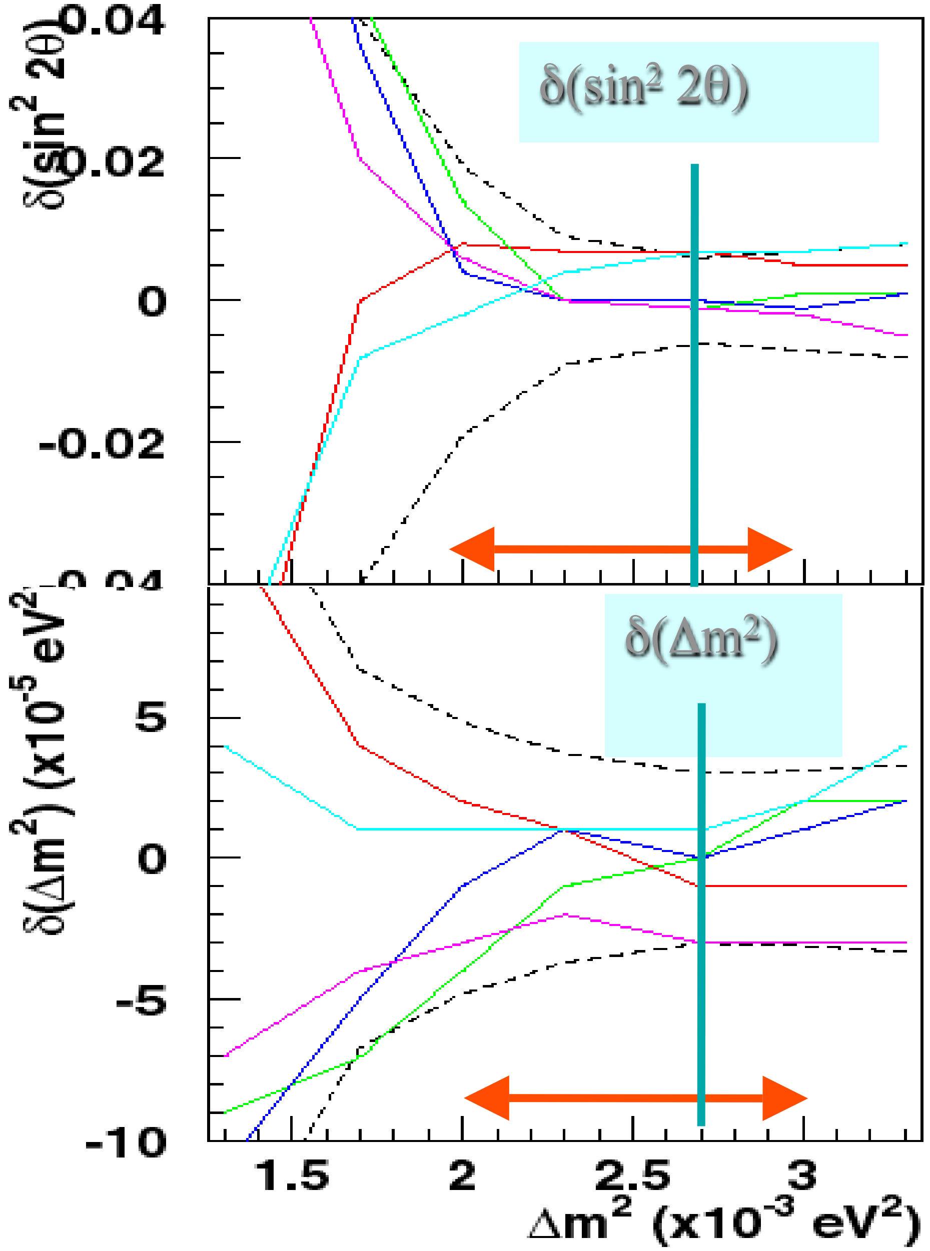


Goal

$\delta(\sin^2 2\theta_{23}) \sim 0.01$

$\delta(\Delta m_{23}^2) \sim < 1\times10^{-4}$

Effect of systematic error on parameter meas.



norm (+5%)

NQE (+5%)

E_{SK} (+1%)

beam shape (±20%)

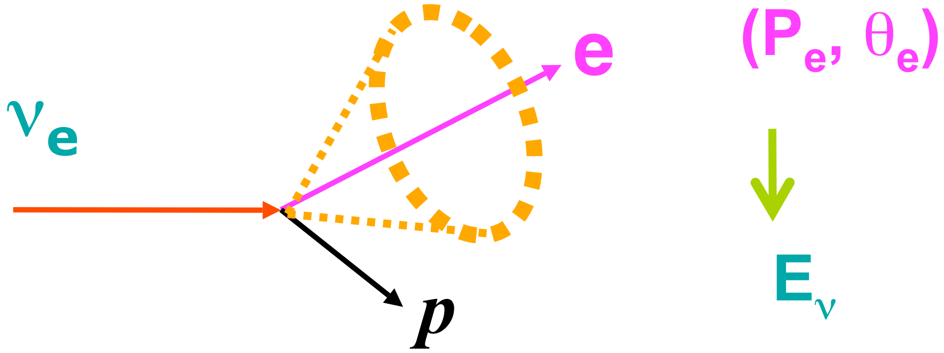
beam width (5%)

Stat. error

T2K Sensitivities (appearance channel)

Discovery of ν_e appearance (θ_{13},Δm_{13})

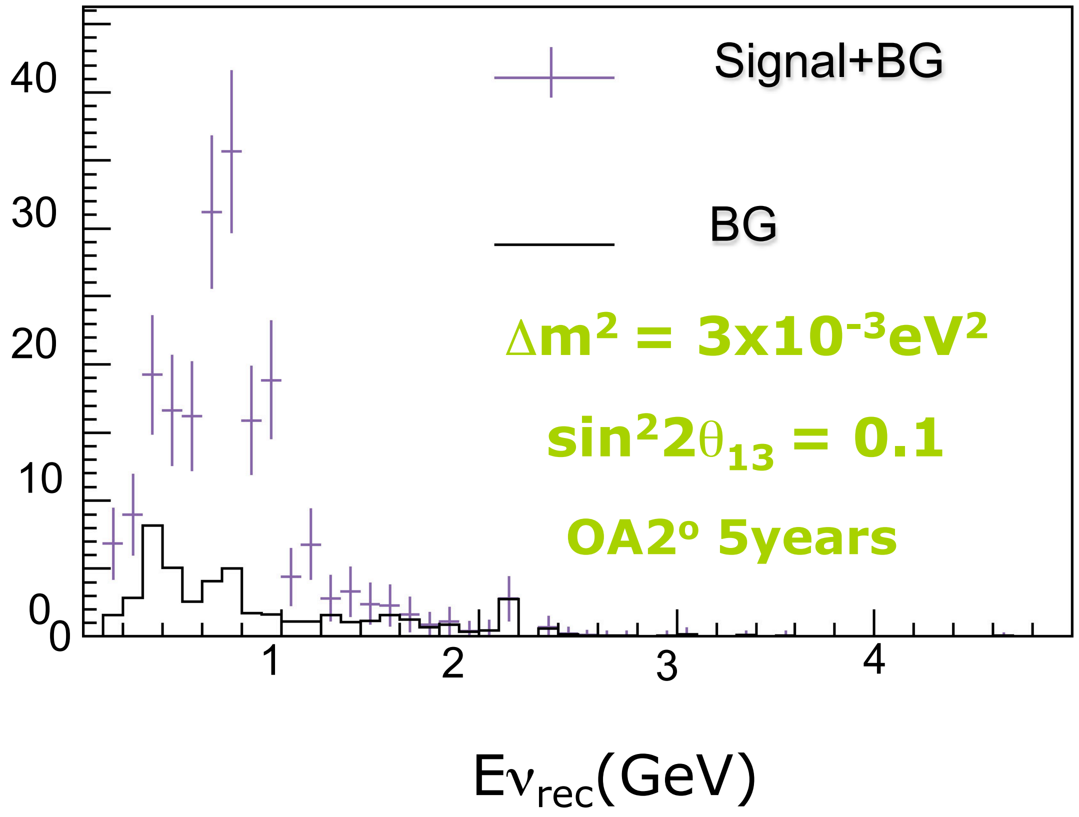
$$P_{\mu \rightarrow e} \approx \sin^2\theta_{23} \times \sin^2 2\theta_{13} \times \sin^2\left(1.27\Delta m_{13}^2 L / E_\nu\right)$$



(P_e, θ_e)

↓

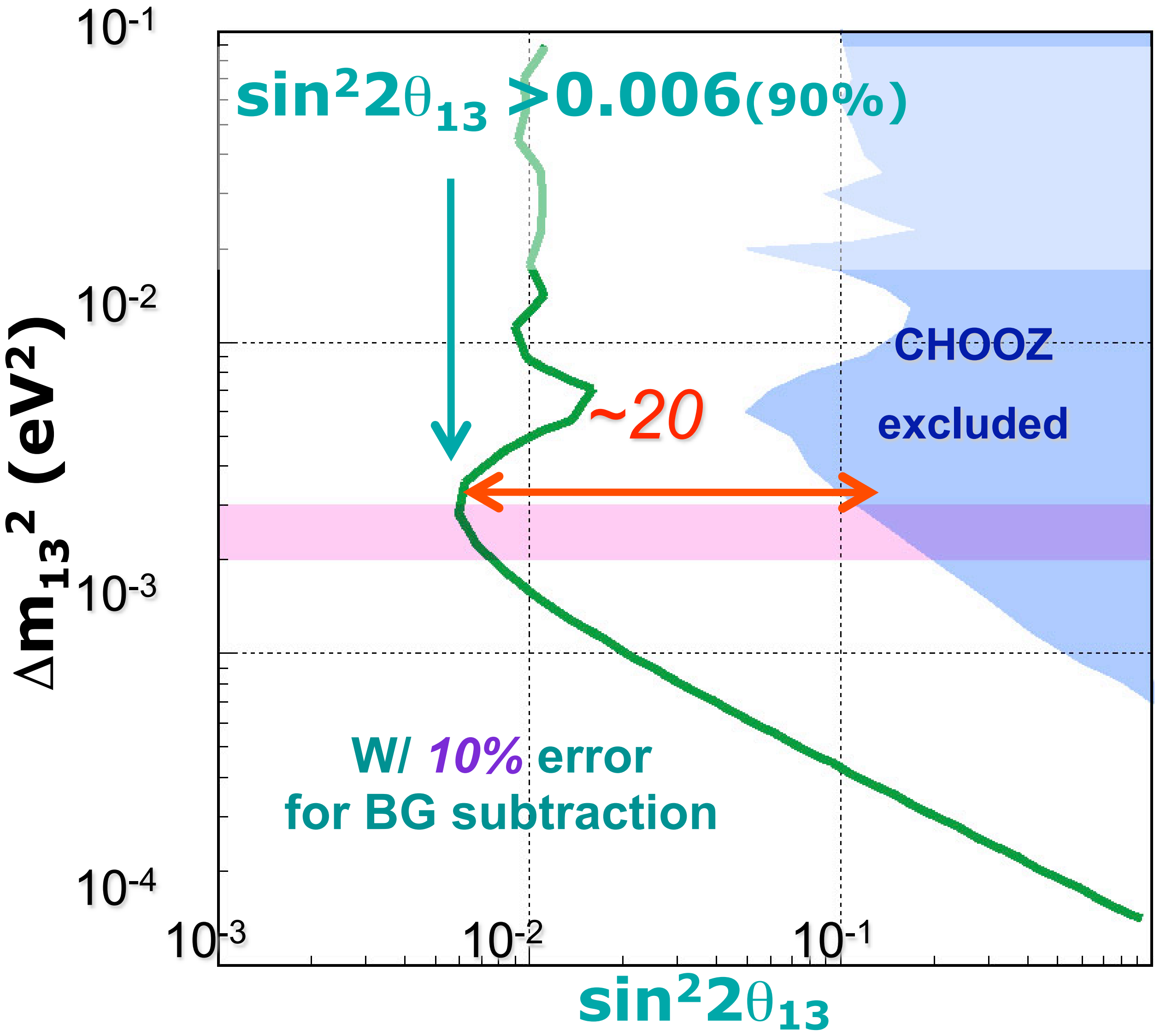
E_ν



$\Delta m^2 = 3\text{x}10^{-3}\text{eV}^2$

$\sin^2 2\theta_{13} = 0.1$

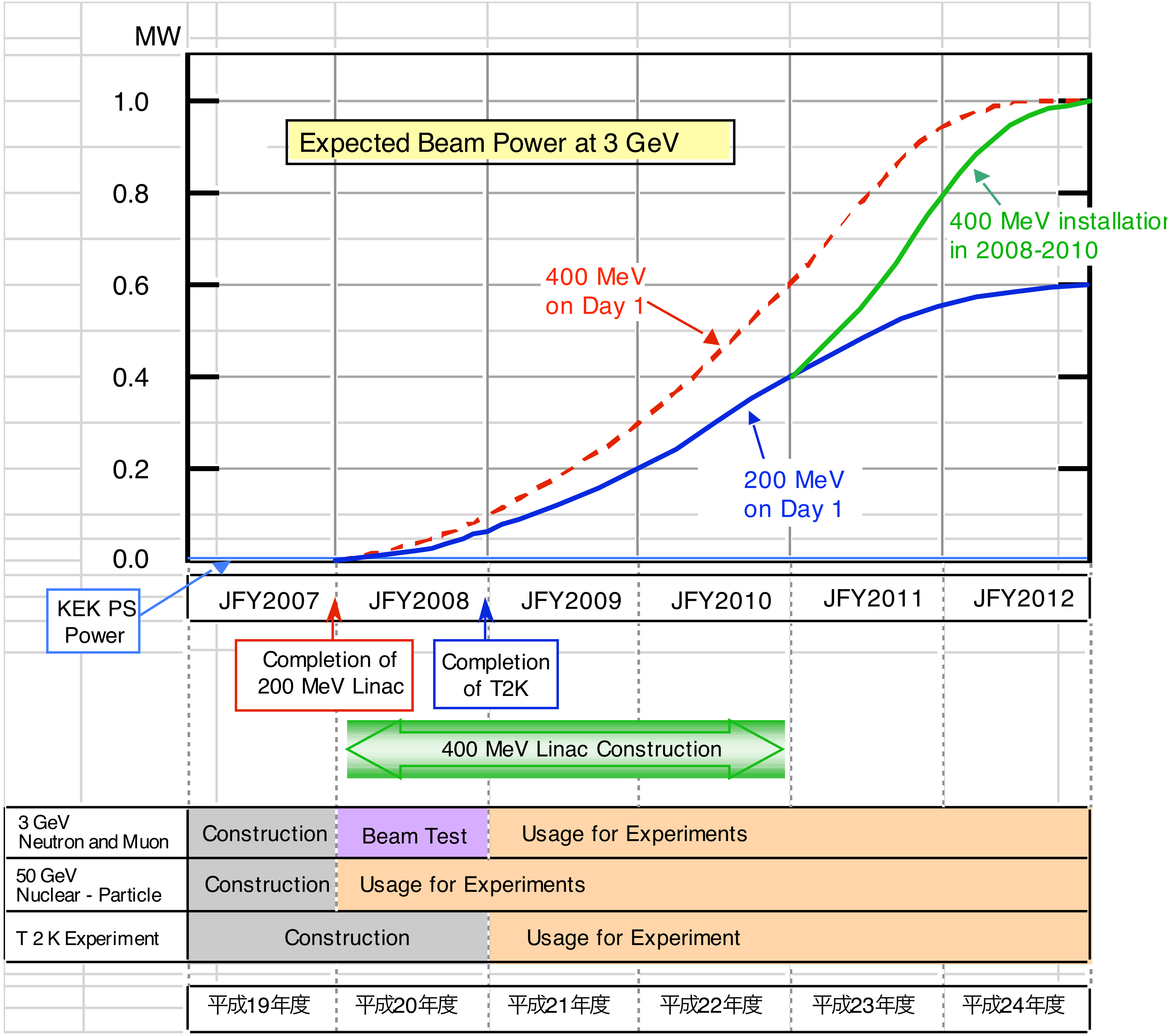
OA2° 5years



W/ *10%* error
for BG subtraction

Assuming $\sin^2\theta_{23}=0.5$, $\delta=0$, no matter

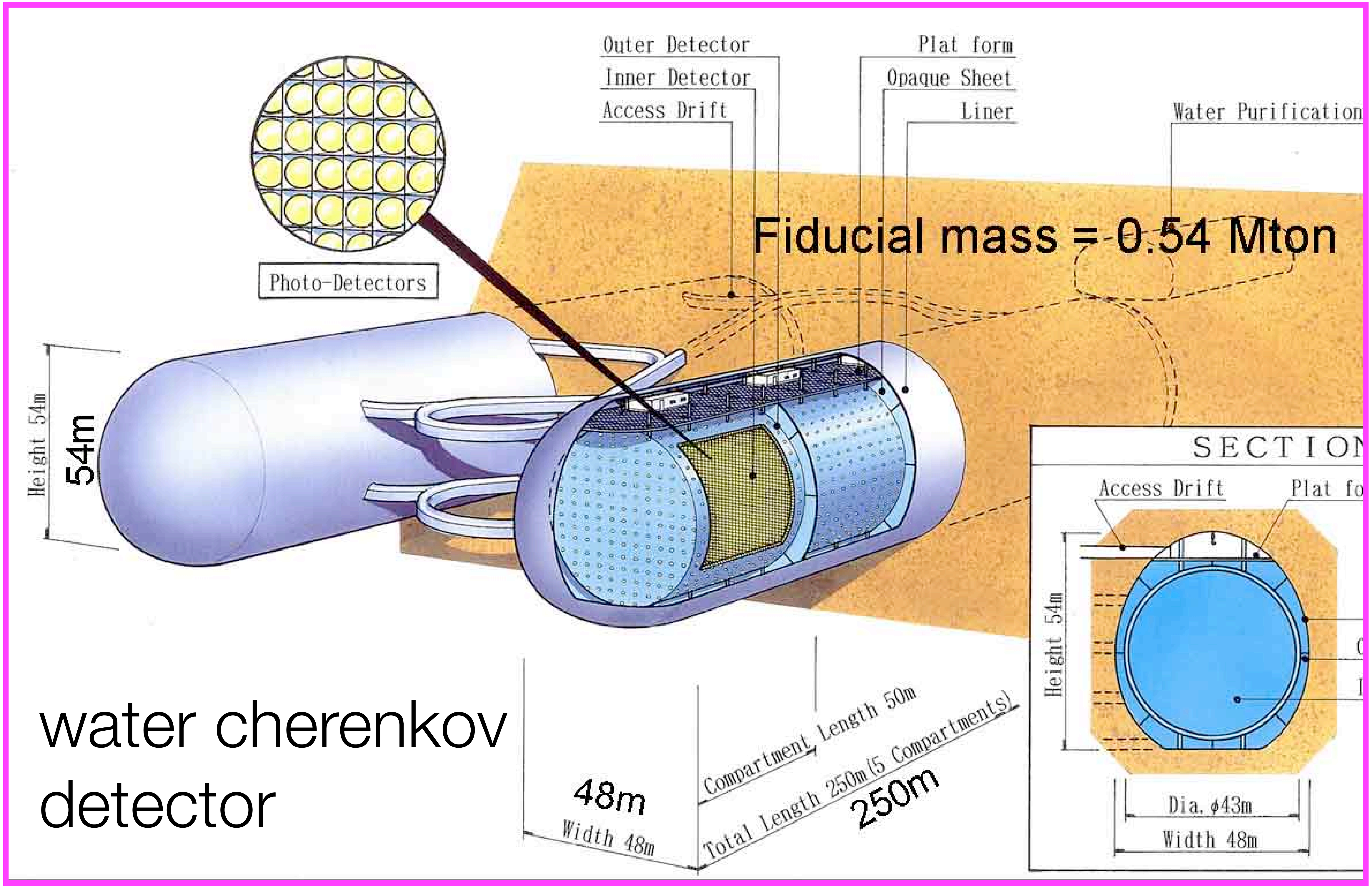
J-PARC Beam Power Improvement Schedule



T2HK

- T2K Phase 2 (future project, not known when)
- Neutrino Source
  - J-PARC upgrade to 4 MW
    - more RF cavities for fast repetition rates.
    - double a number of bunches with barrier buckets.
- Neutrino Detector
  - Hyper Kamiokande
    - 1 M ton total mass (0.5 Mton fiducial total volume)
    - 2 detector 48m x 50m x 250m

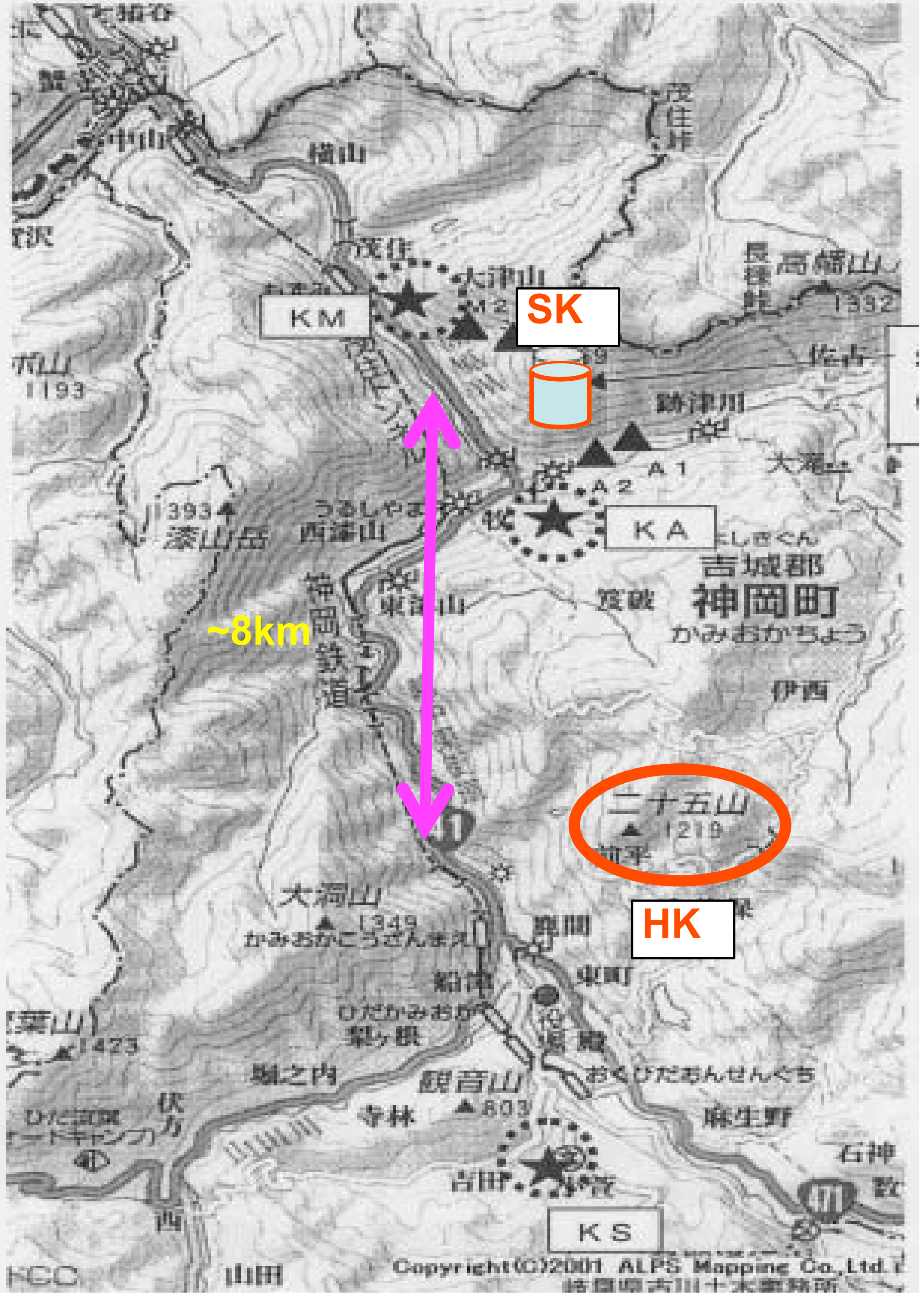
Hyper Kamiokande



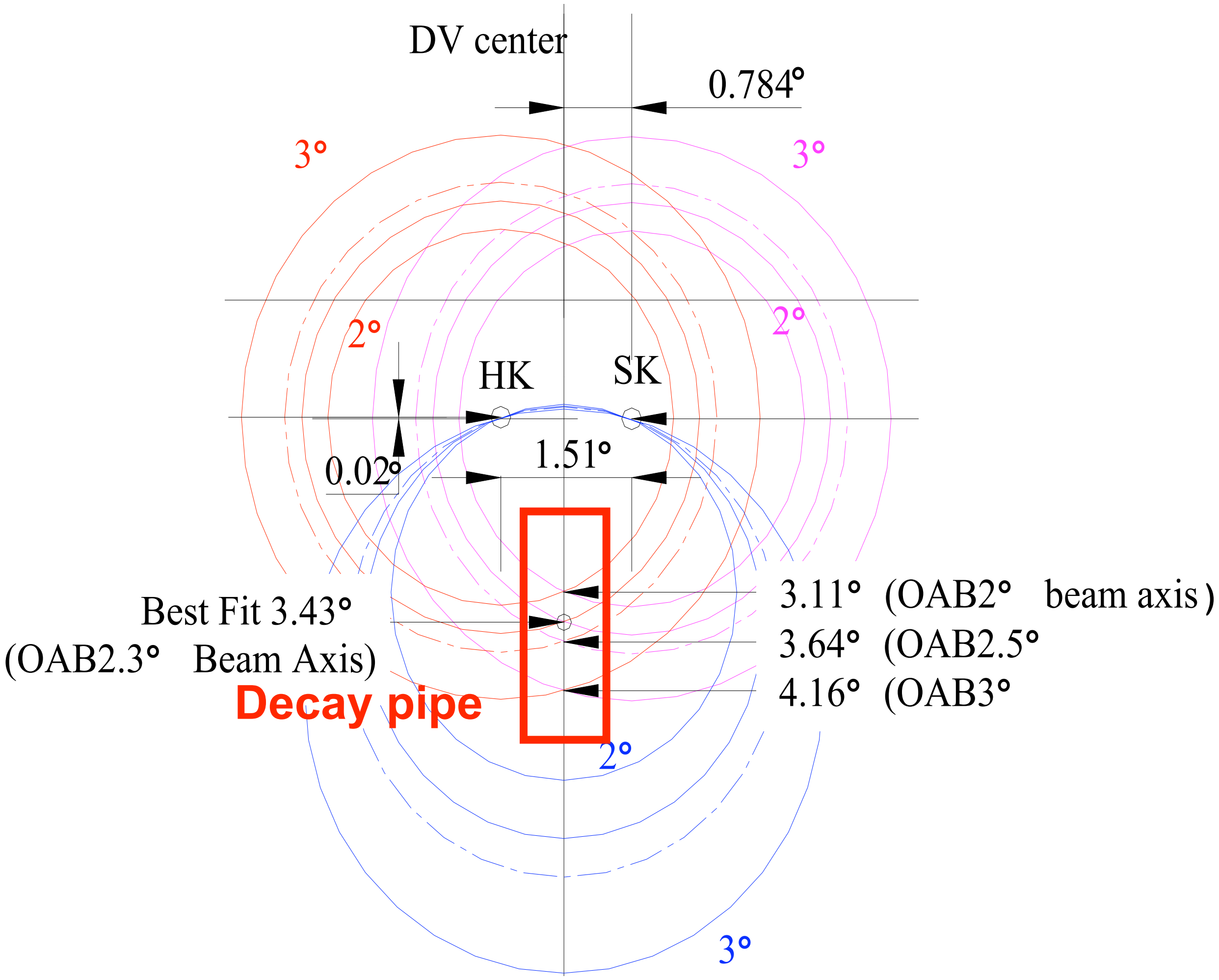
Fiducial mass = 0.54 Mton

water cherenkov detector

Decay Pipe for SK/HK Off-axis Beam Coverage



Beam eye



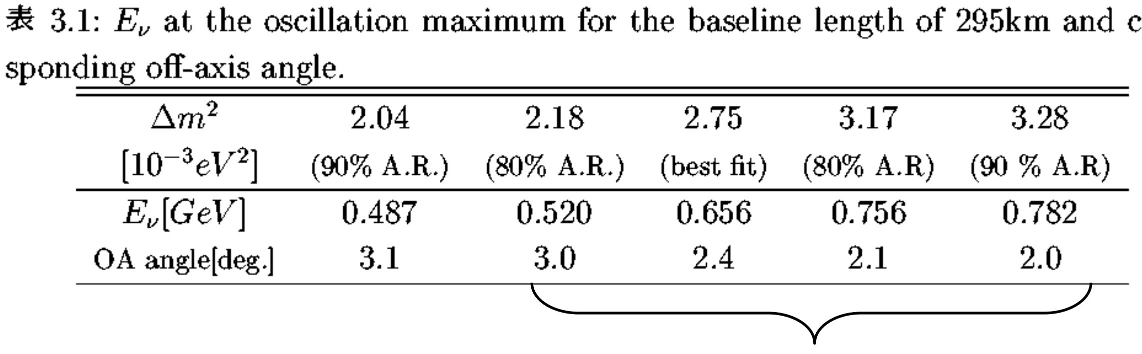


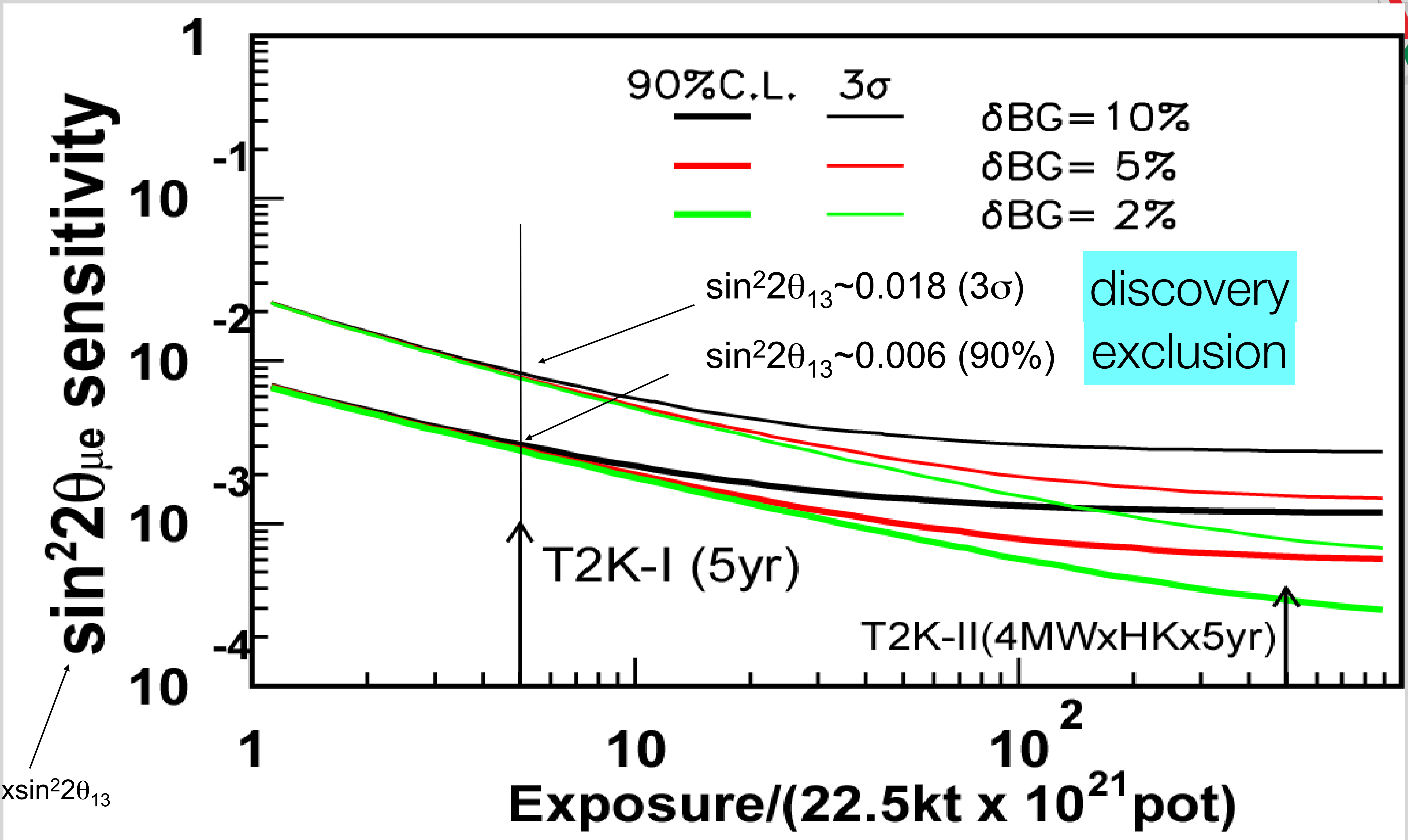
表 3.1: E_ν at the oscillation maximum for the baseline length of 295km and corresponding off-axis angle.

Δm^2 $[10^{-3}eV^2]$	2.04 (90% A.R.)	2.18 (80% A.R.)	2.75 (best fit)	3.17 (80% A.R)	3.28 (90 % A.R)
$E_\nu[GeV]$	0.487	0.520	0.656	0.756	0.782
OA angle[deg.]	3.1	3.0	2.4	2.1	2.0

Cover this region

Comments :
Exclusion and Discovery Sensitivities

- Experimental sensitivities of search can be categorized in two ways.
- Exclusion sensitivity (Upper limit) :
  - the upper limit value of given confidence level from a zero value when no signals are found.
- Discovery sensitivity (Discovery limit) :
  - the probability to discover a non-zero value and to exclude a zero value with given confidence level.
  - the probability that the observed signal is not due to background fluctuation with given confidence level.



$\sin^2 2\theta_{13}$~0.018 (3σ)

$\sin^2 2\theta_{13}$~0.006 (90%)

discovery

exclusion

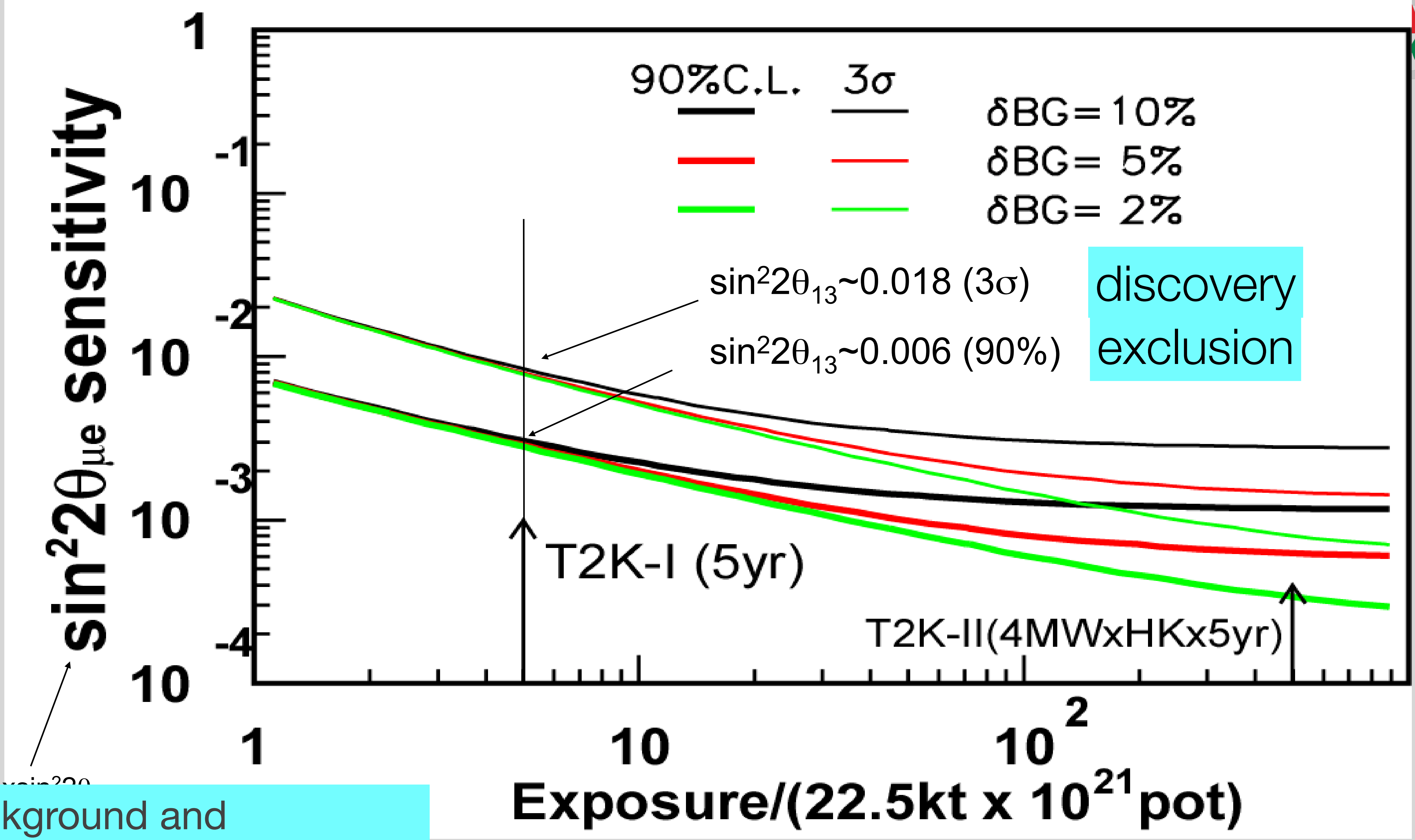
T2K-I (5yr)

T2K-II(4MWxHKx5yr)

0.5x$\sin^2 2\theta_{13}$

T2HK Sensitivity

T2HK Sensitivity



Background and systematics are required to be much less than 10 %.

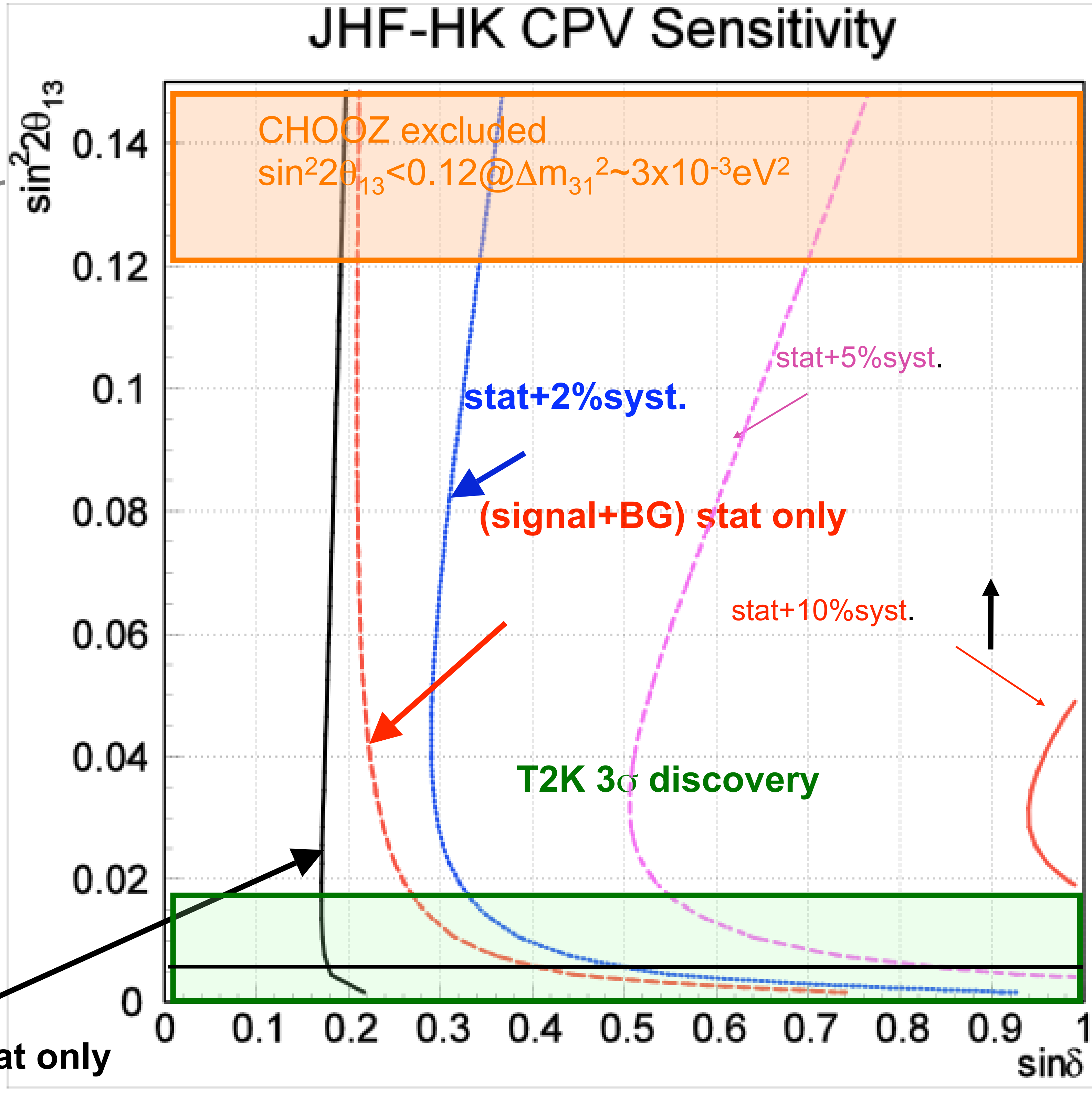
$$A_{CP} \approx \frac{\Delta m_{12}^2}{4E_\nu} \times \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \times \sin\delta$$

$\Delta m_{21}^2=6.9\times10^{-5}eV^2$
$\Delta m_{32}^2=2.8\times10^{-3}eV^2$
$\theta_{12}=0.594$
$\theta_{23}=\pi/4$

T2HK - CP Sensitivity

- Sensitivity
  - 3 sigma discovery
- Neutrino Source and Detector
  - 4 M Watt Proton beam power
  - 550 kton fiducial volume
- Running Conditions
  - 2 year neutrinos
  - 6-7 years anti-neutrinos
- Background and systematic error are important.

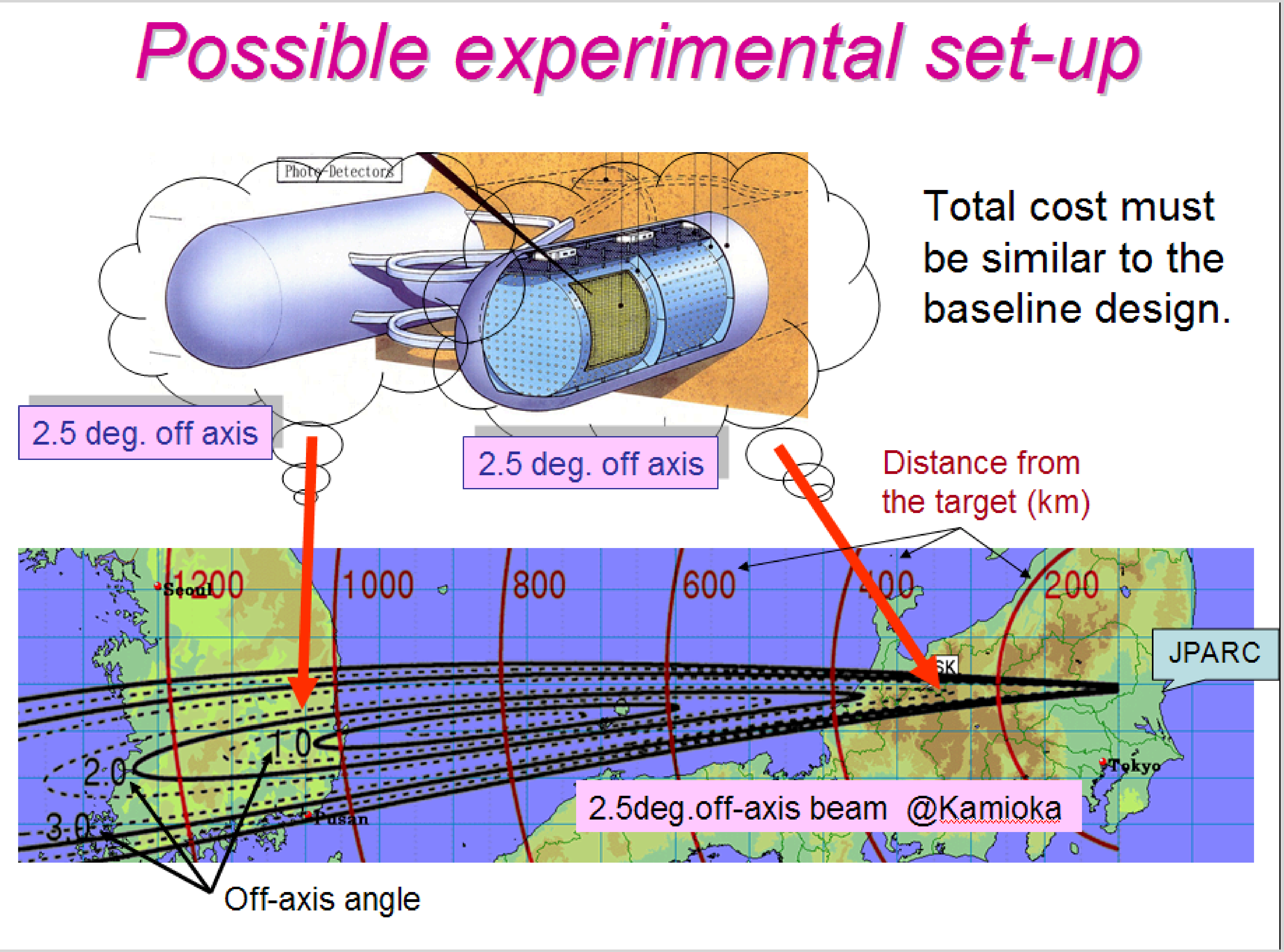
3σ CP sensitivity : $|\delta|>20^o$ for $\sin^2 2\theta_{13}>0.01$ with 2% systematic error.



no BG
signal stat only

T2KK

- T2KK = a long baseline neutrino oscillation from Tokai to Kamioka and Korea
- Motivations
  - Achieve good CP sensitivity with reasonable systematic errors (not 2%).
  - self-determined mass hierarchy (long baseline)
- Advantages :
  - CP effect is proportional to L/E (larger in Korea).
  - Matter effect is large for longer baseline (larger in Korea).
  - 10 % systematics
- Limitations :
  - Less event rates at Korea.

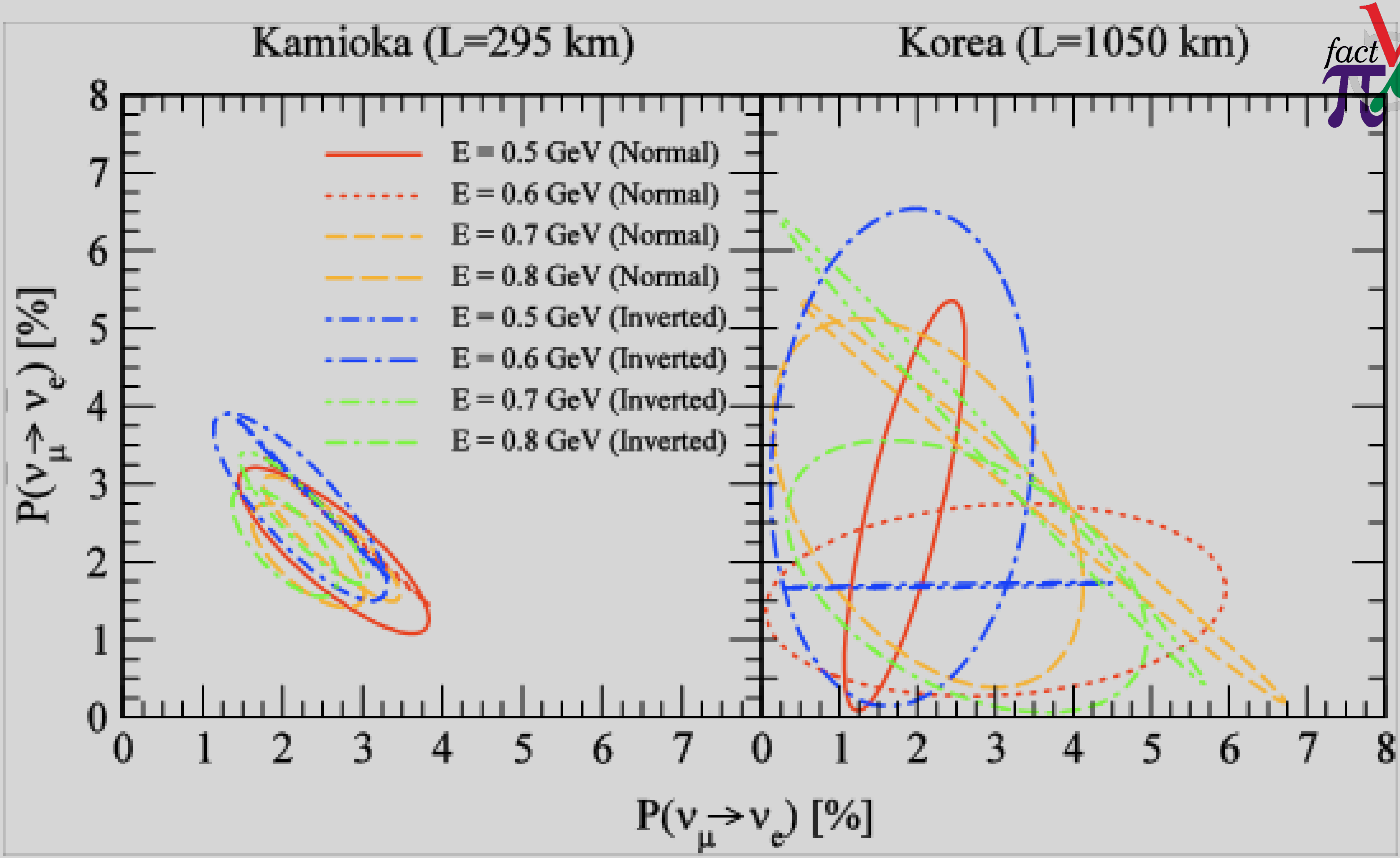


Possible experimental set-up

Total cost must be similar to the baseline design.

T2KK Experimental Setup

2.5 degree off axis for both Kamioka and Korea.
same spectra for both.

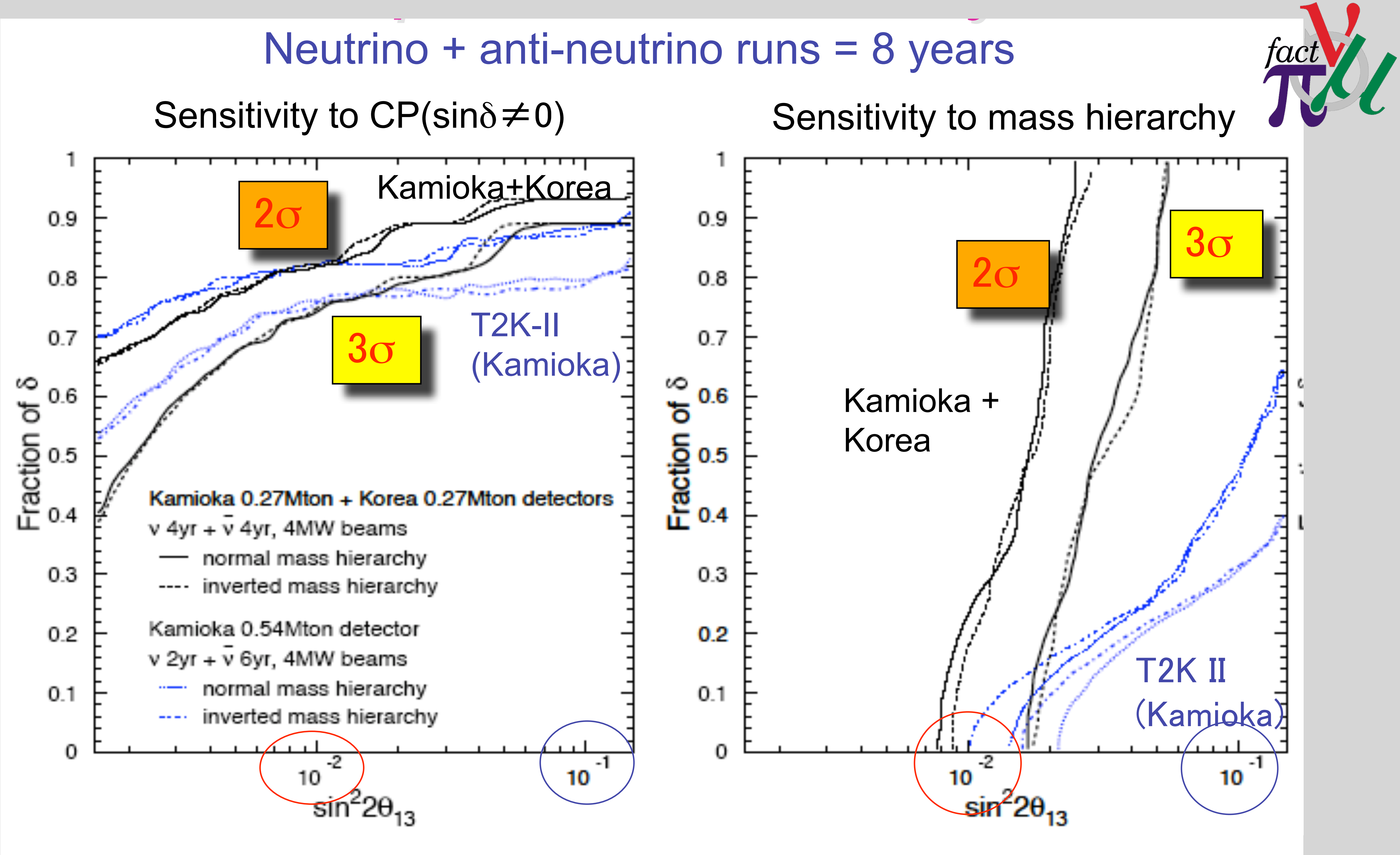


Bi-Probability at Kamioka and Korea

normal or inverted

Comments :
Sensitivity Definitions

- Fraction of δ(CP)
  - what fraction of all possible δ(CP) values the value of interested can be discovered.
  - Larger fraction of coverage δ(CP) has better sensitivity

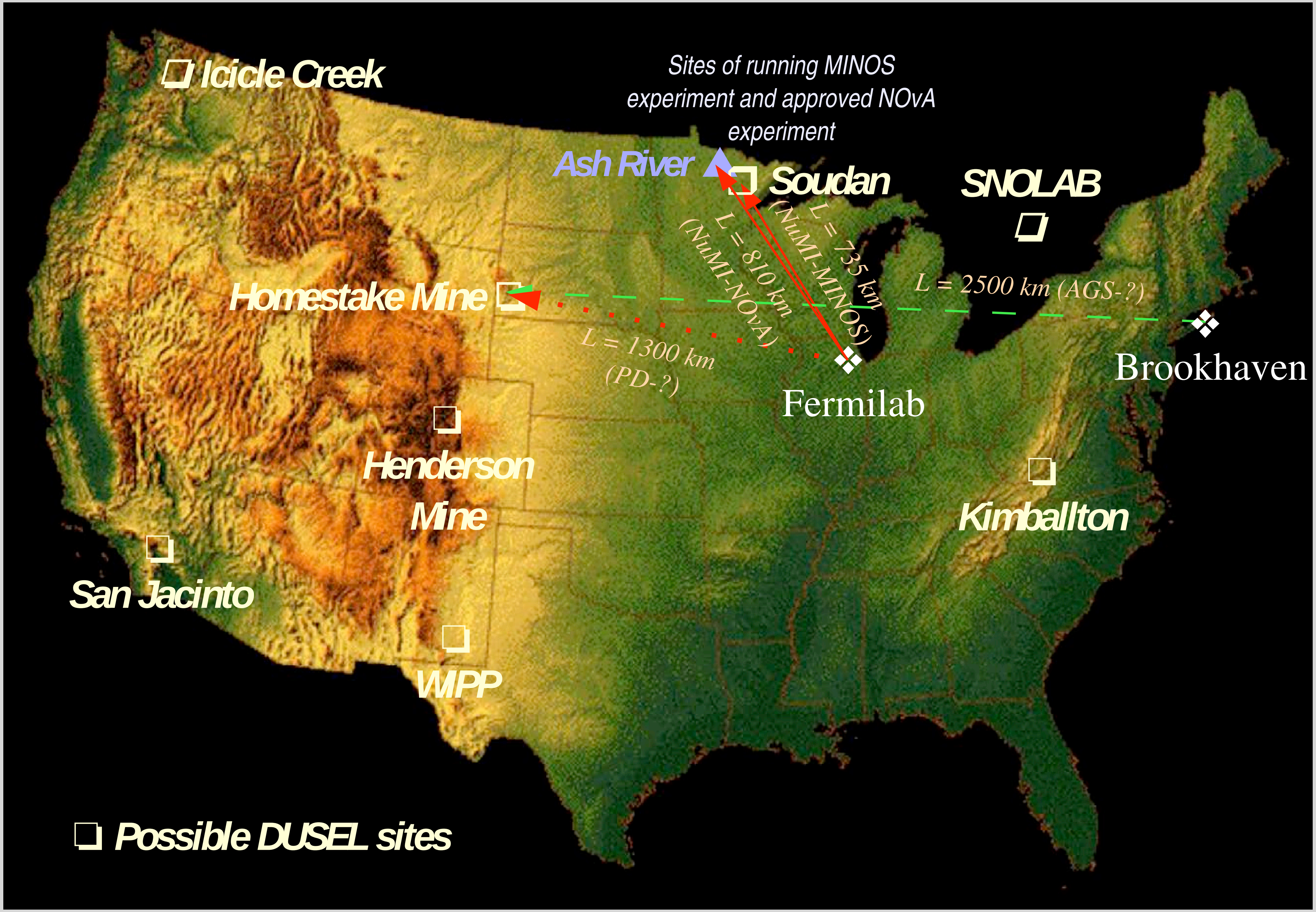


Neutrino + anti-neutrino runs = 8 years

Sensitivity to CP(sinδ≠0)

Sensitivity to mass hierarchy

T2KK Sensitivity

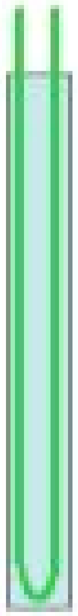


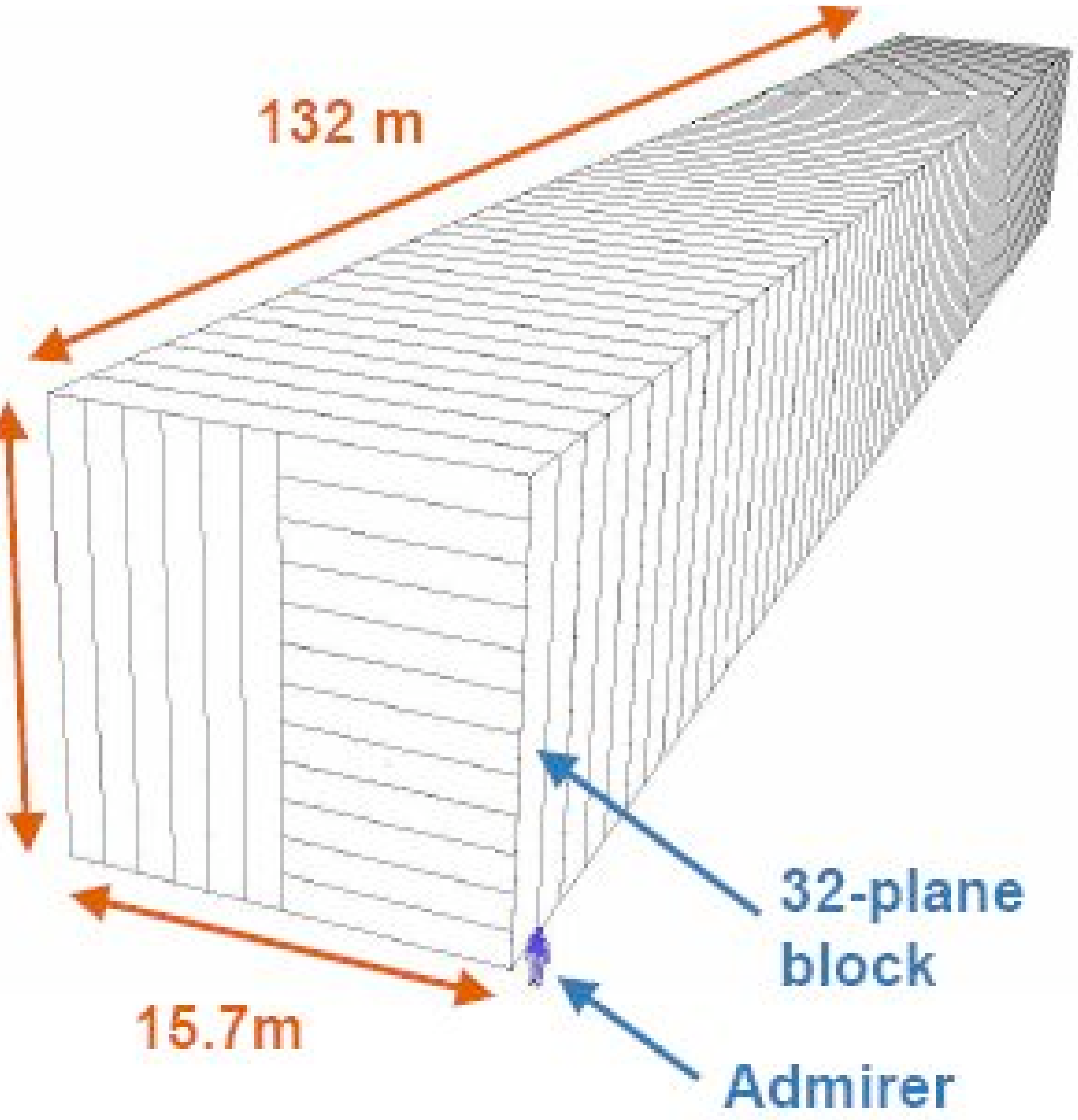
Superbeams in the United States

MINOS (not mentioned)
NOvA (mentioned a little)
BNL-Homestake

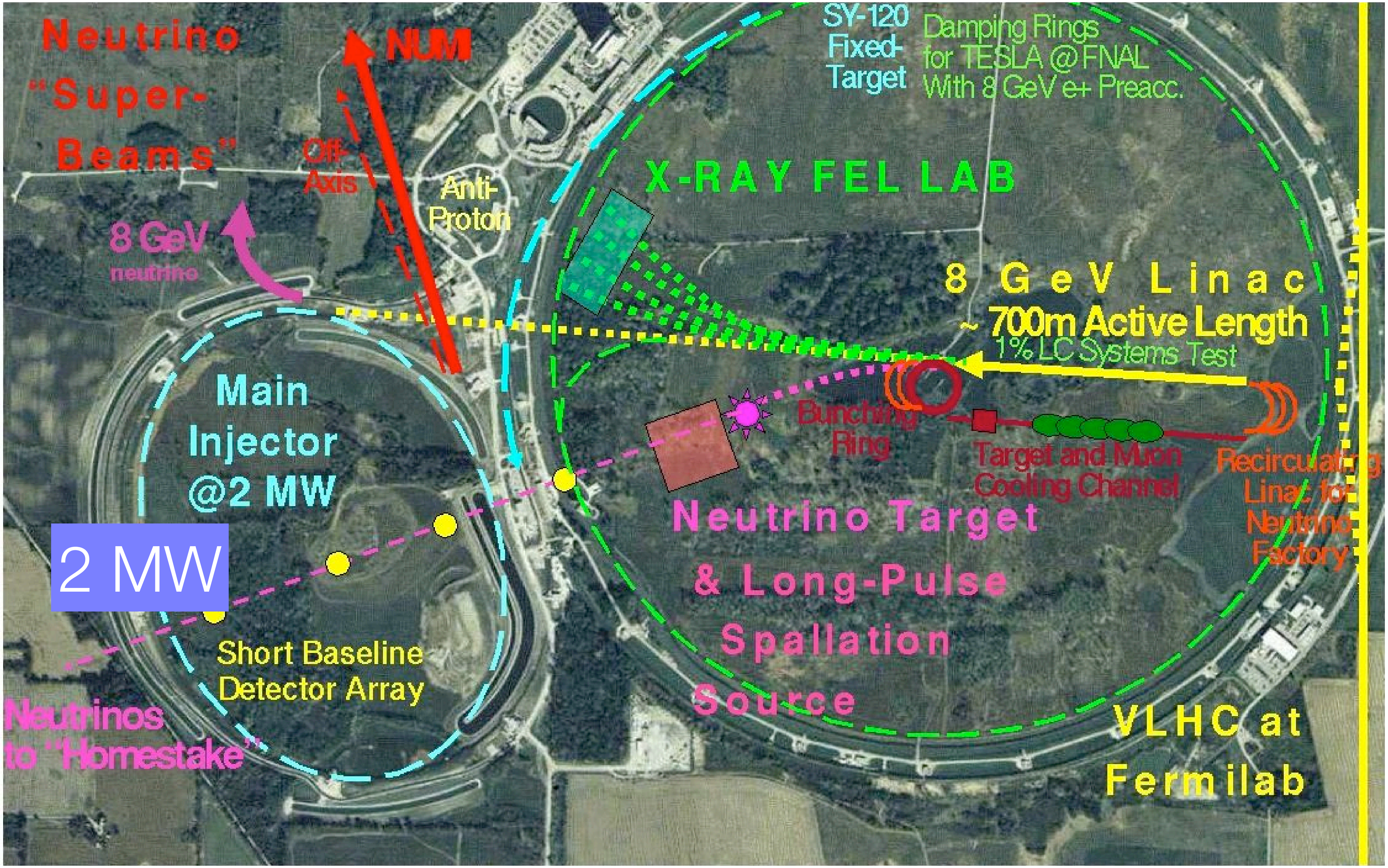
NOvA Detector

“Totally Active”
30 kT:
  24 kT liquid scintillator
  6 kT PVC
32 cells/extrusion
12 extrusions/plane
1984 planes
Cell dimensions:
  3.9 cm x 6 cm x 15.7m
  (0.15 X_0 thickness)
Extrusion walls:
  3 mm outer
  2 mm inner
U-shaped 0.8 mm WLS
fiber into APD



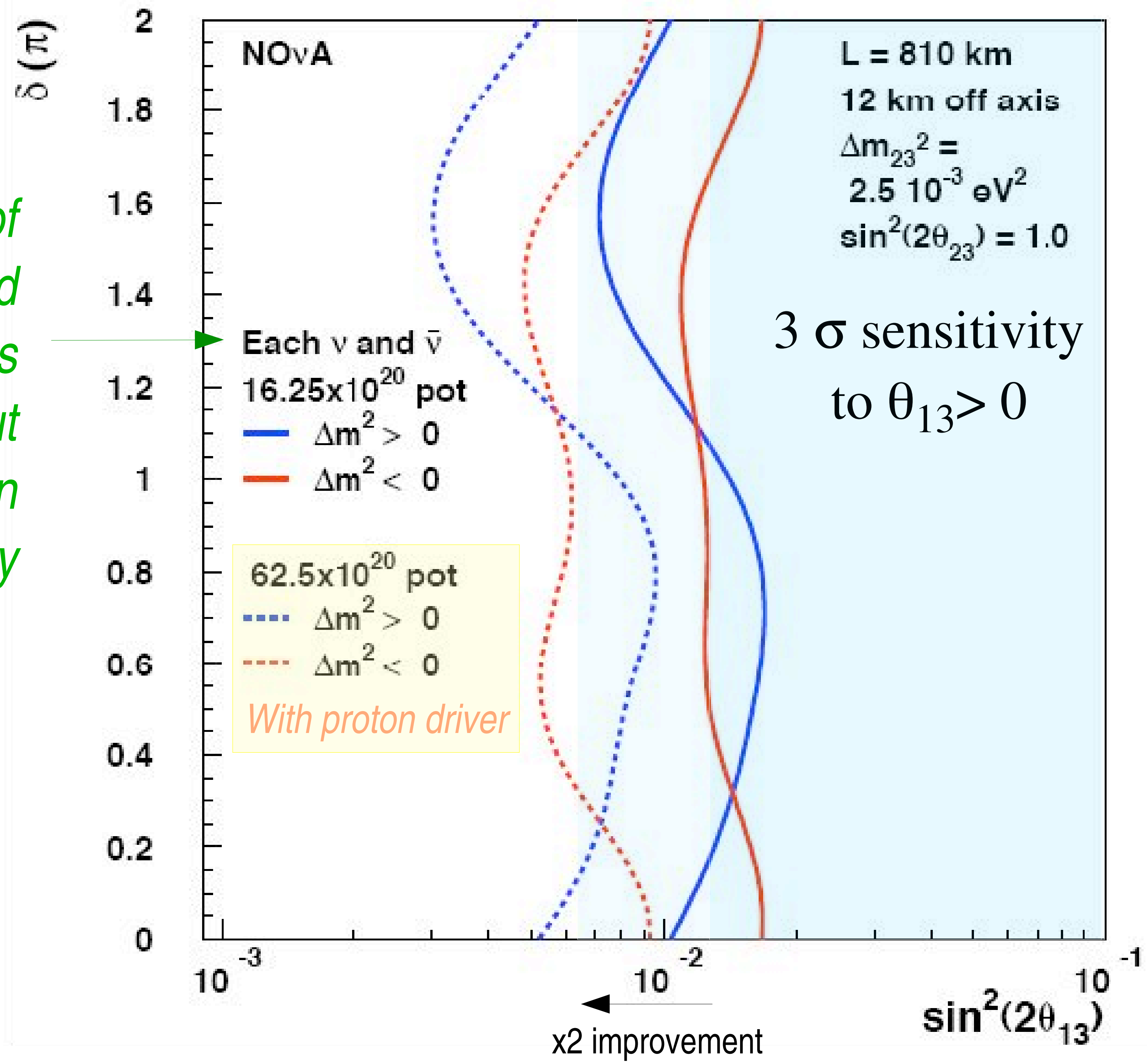


New Proton Driver at Fermilab



NOvA Sensitivity with new FNAL Proton Driver

Mixture of neutrinos and anti-neutrinos evens out variations in sensitivity

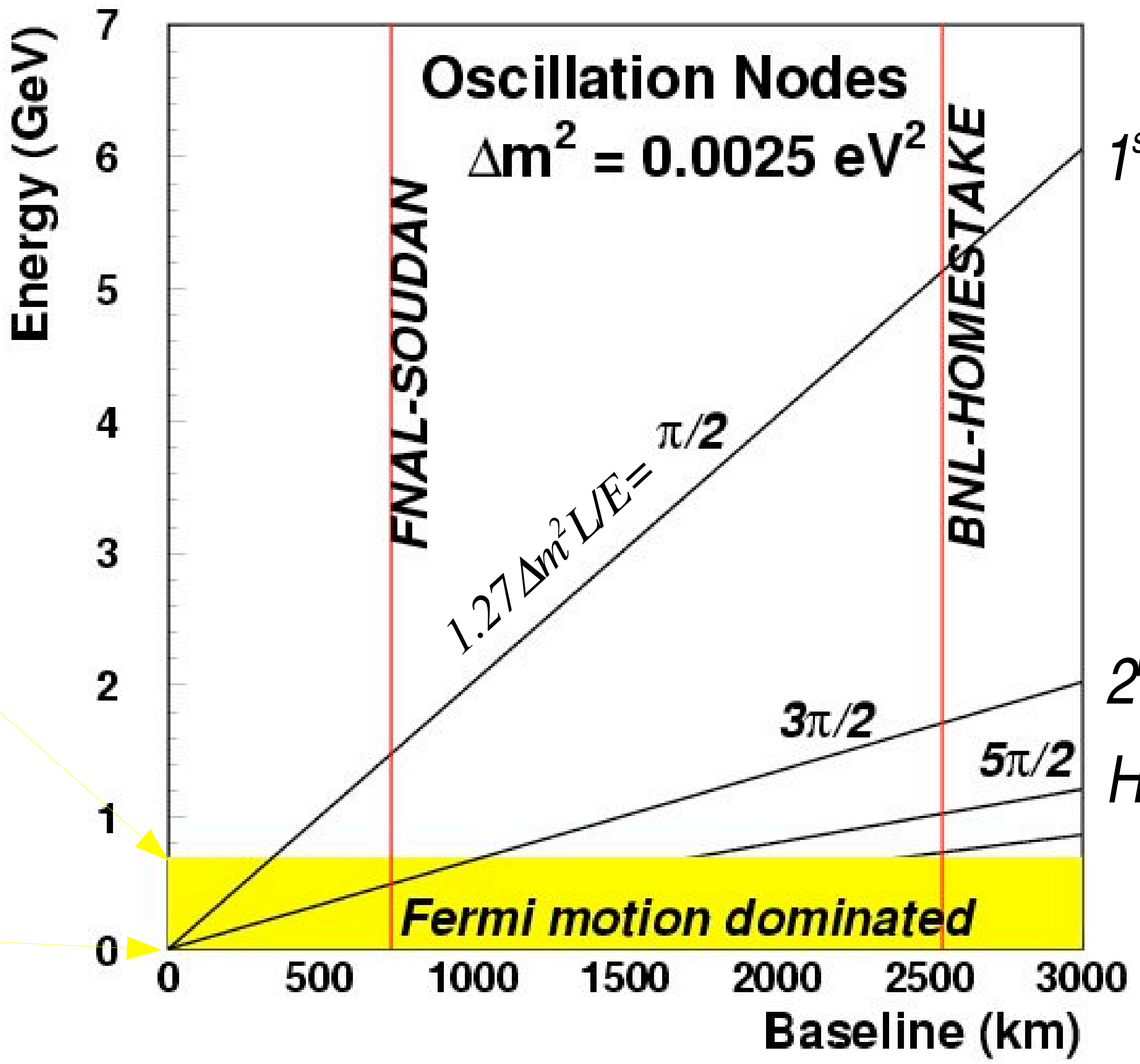


x2 improvement
in sensitivity

Gary Feldman WIN'05

The “very” Long Baseline Idea

- Very long baseline moves 2nd oscillation maximum to an energy where it can be resolved.
- Matter effect increases (to resolve mass hierarchy).
- Larger CP asymmetry (~L) compensates for decreased statistics (~1/L^2).



1st oscillation maximum

2nd oscillation maximum

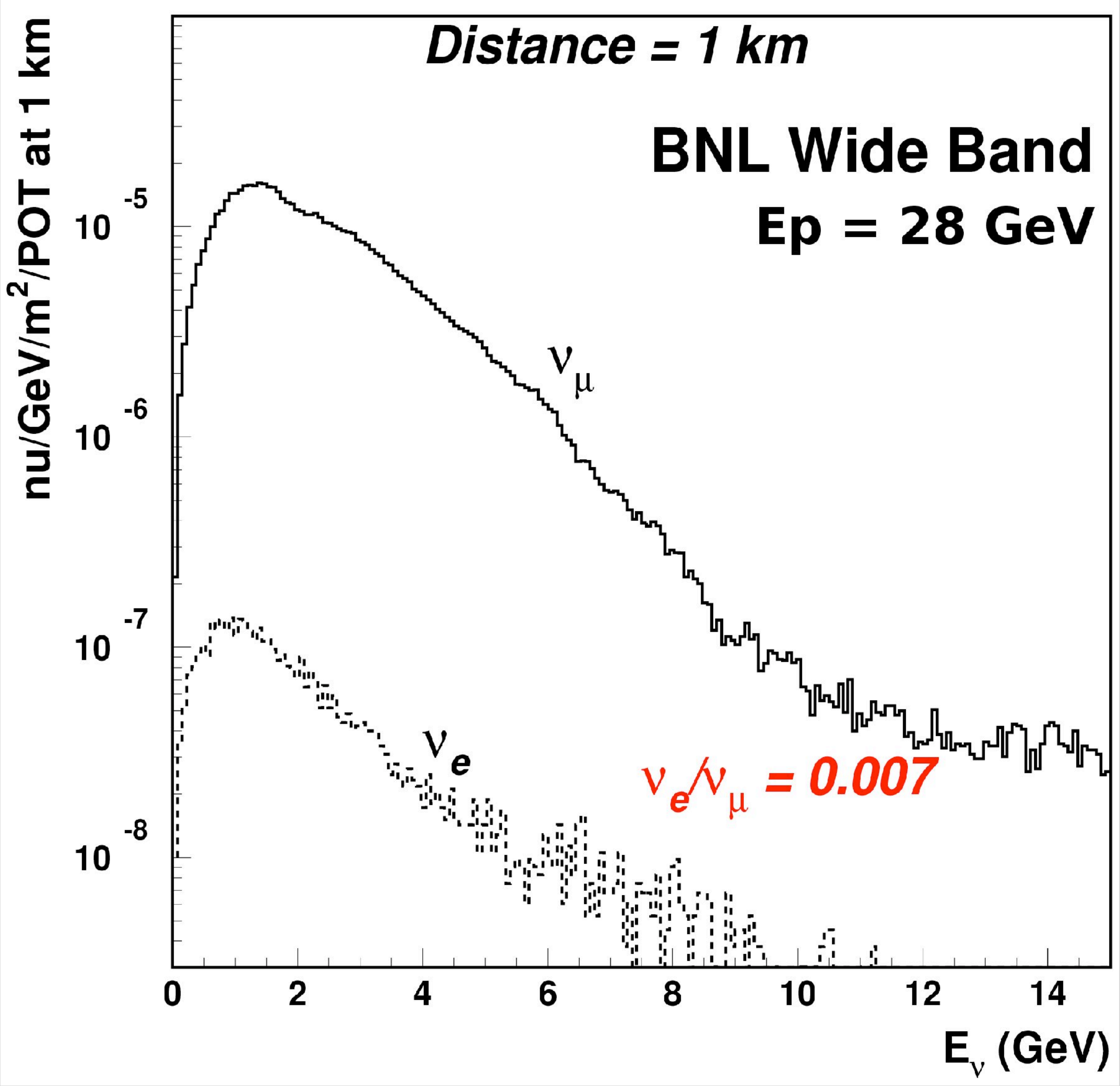
Higher order maxima

~200 MeV Fermi motion degrades neutrino energy resolution

Neutrino Beam from Upgraded AGS

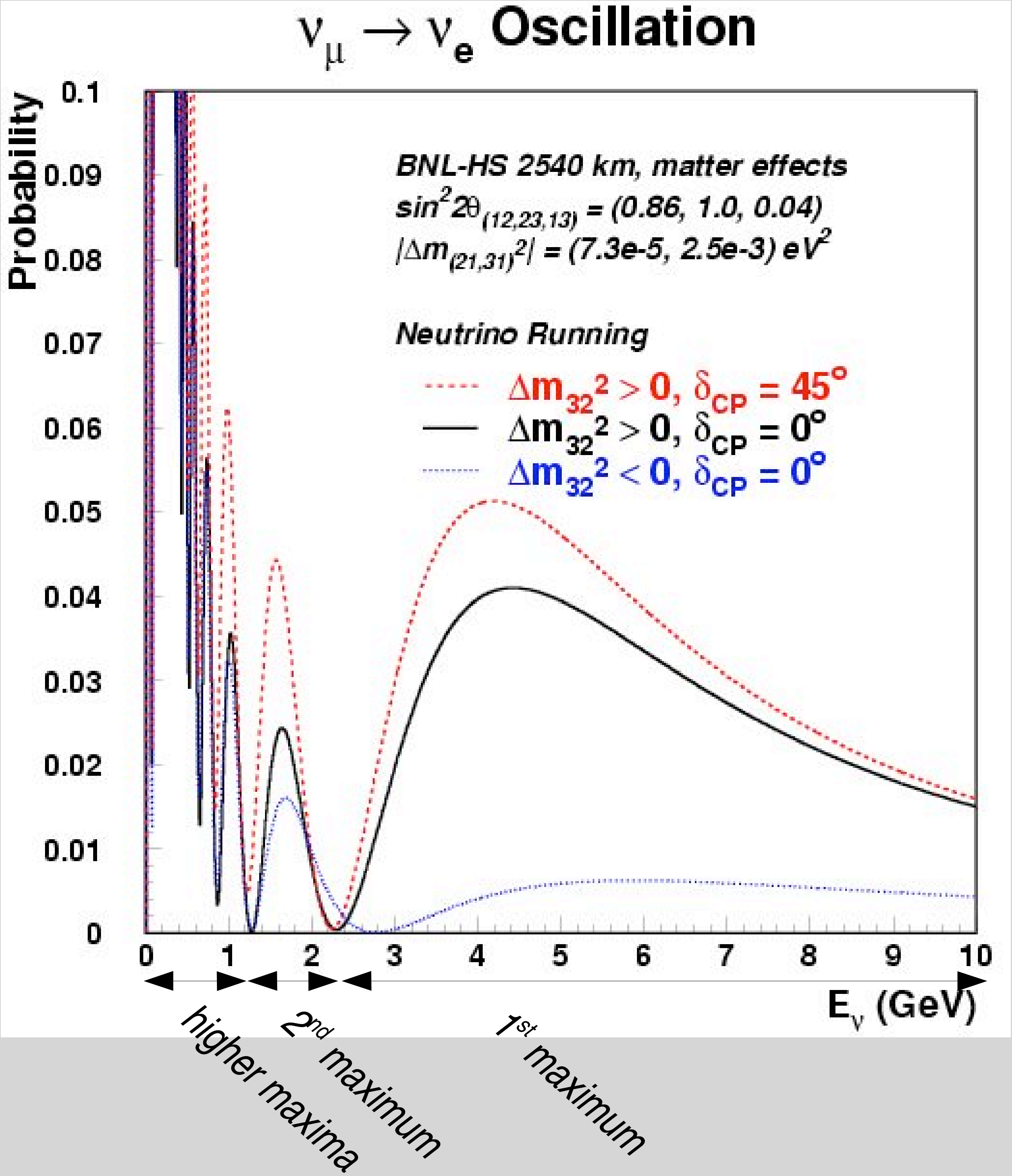
- Upgrade of the AGS 28 GeV proton sources from 0.14 MW to 1 MW.
  - modest increase from 7E13 protons per pulse to 9E13 protons per pulse
  - A factor of 5 increase in repetition rate from 0.5 Hz to 2.5 Hz.
    - new power supplies and RF
    - a new 1 GeV superconducting linac

Wide Band Beam

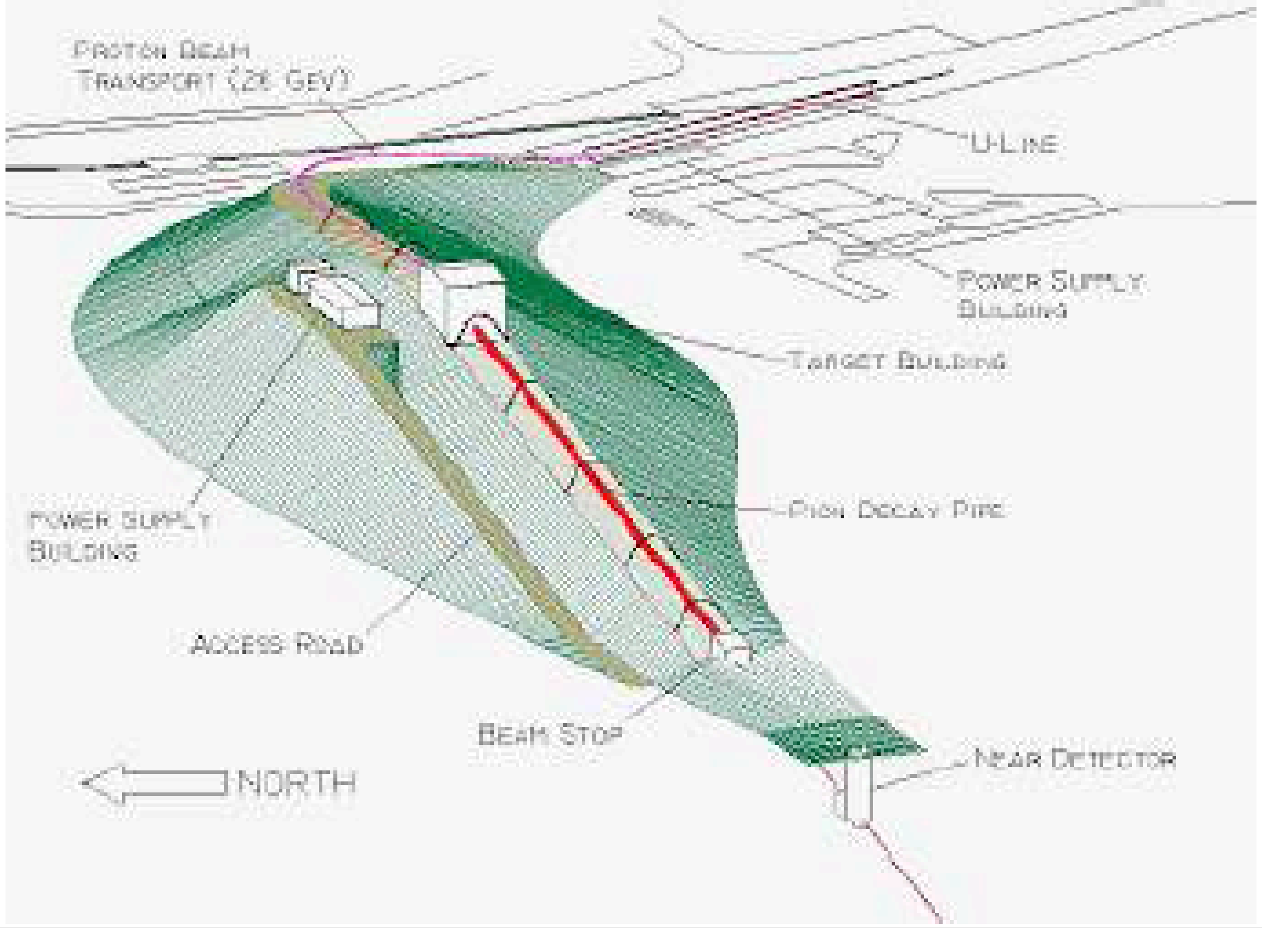


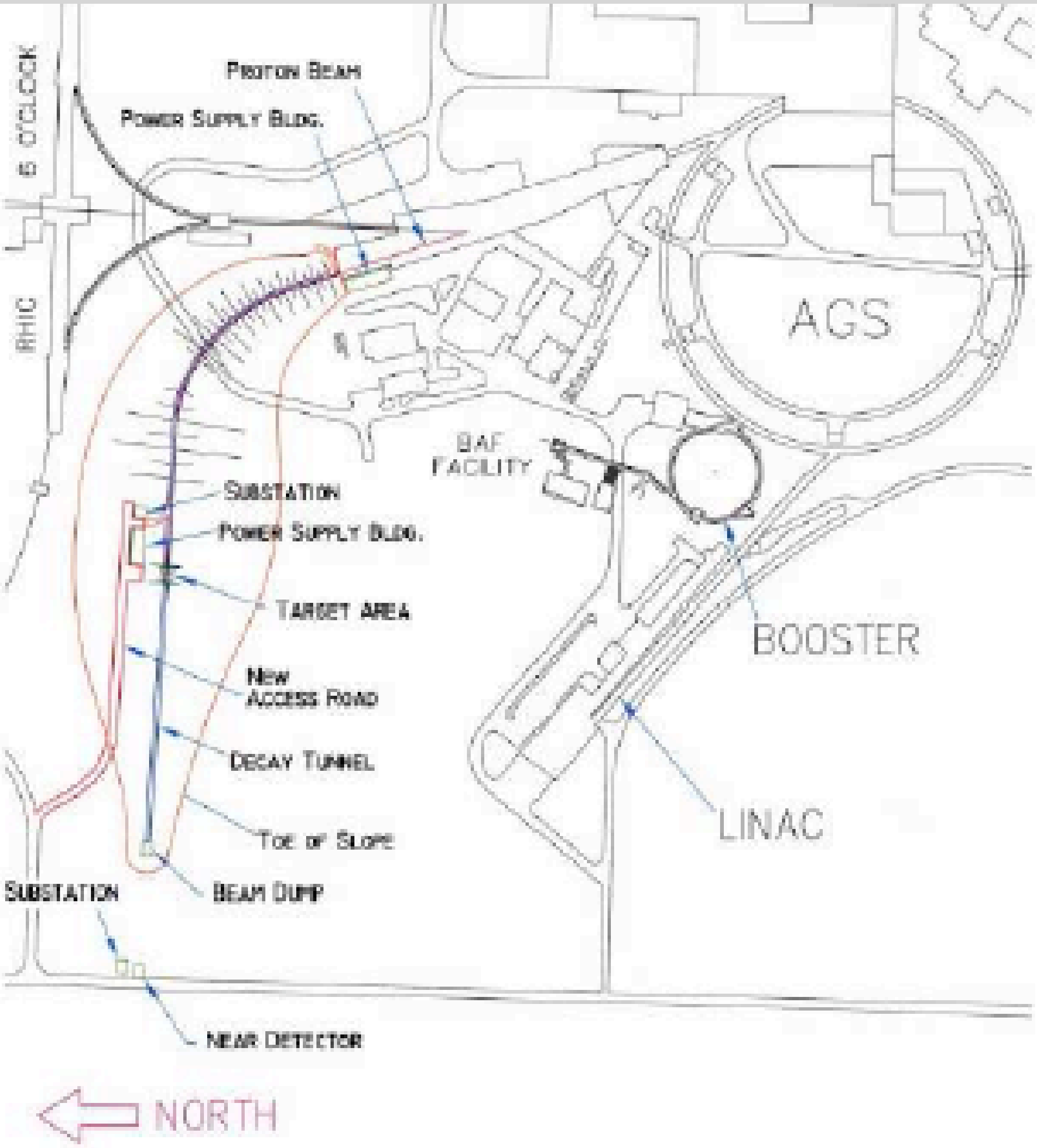
Oscillation Probability for BNL-Homestake

- Use a wide band beam to cover three energy regions.
- 1st maximum region
  - sensitive to mass hierarchy.
- 2nd maximum region
  - stronger CP asymmetry
- Higher maxima region
  - sensitive to solar oscillation.

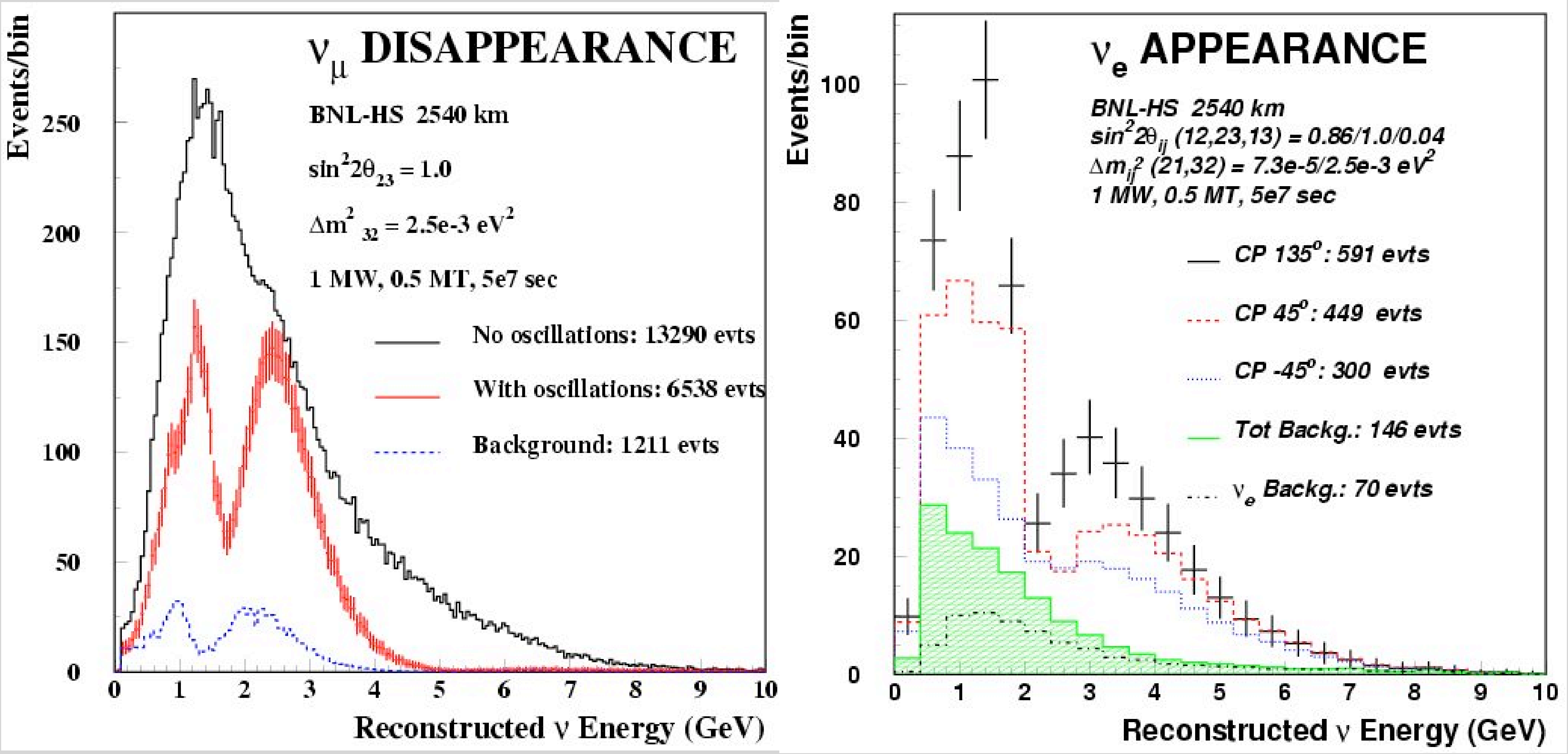


higher repetition rates (2.5Hz)
with superconducting linac.
average beam power 1MW





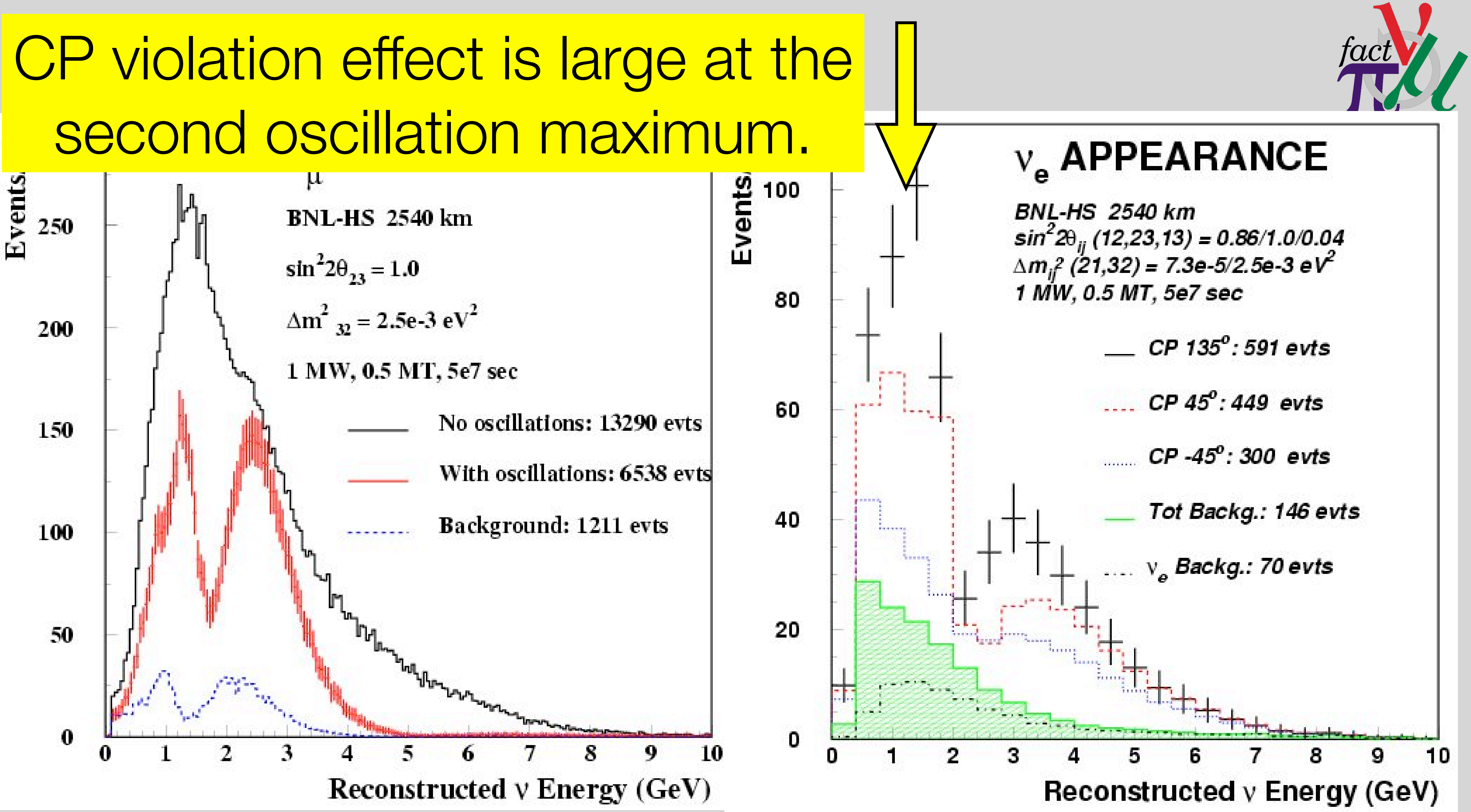
Proposed BNL-Homestake Beam Line



BNL-Homestake Event Spectra

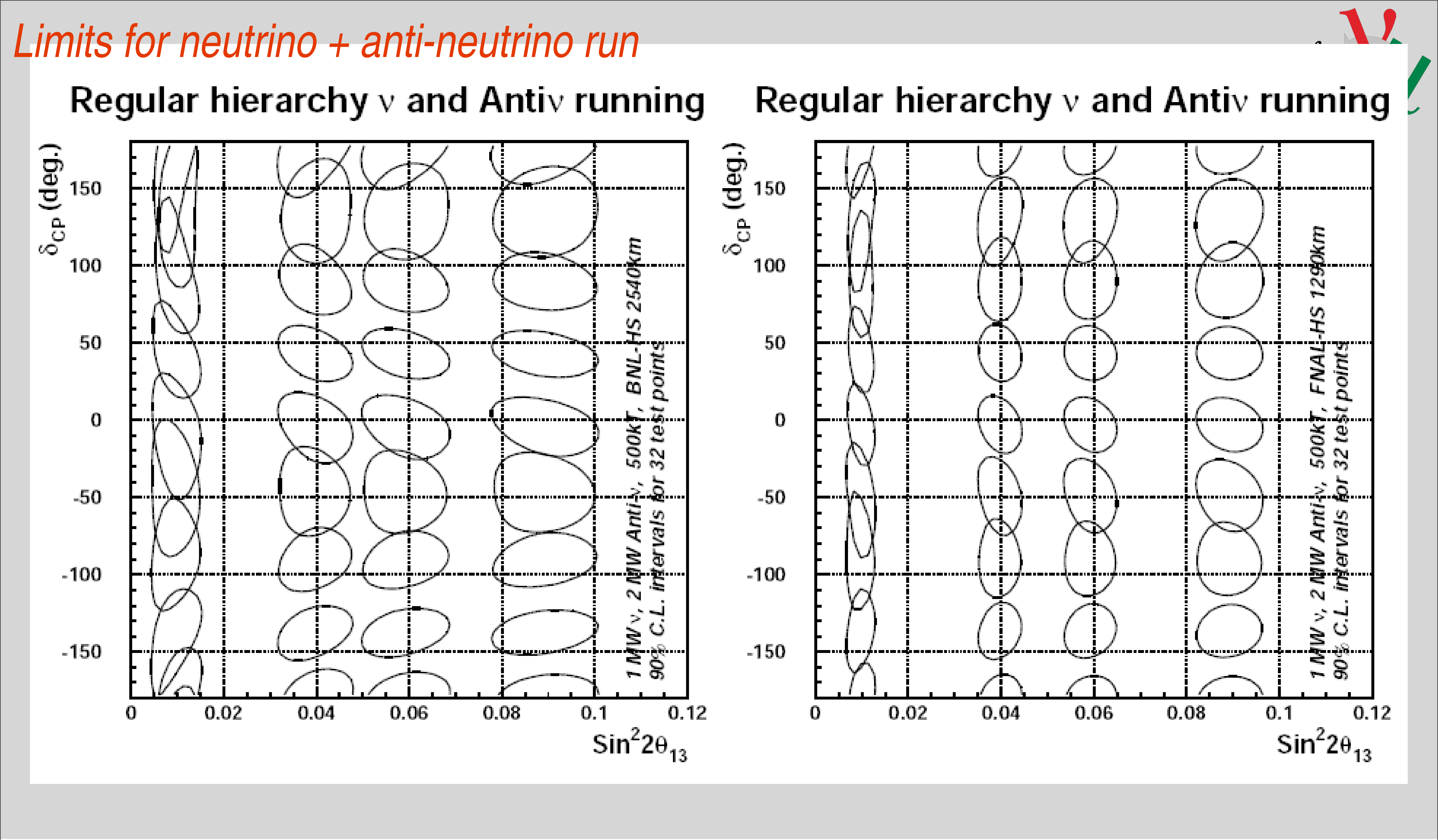
Single neutrino run

CP violation effect is large at the second oscillation maximum.



BNL-Homestake Event Spectra

Single neutrino run



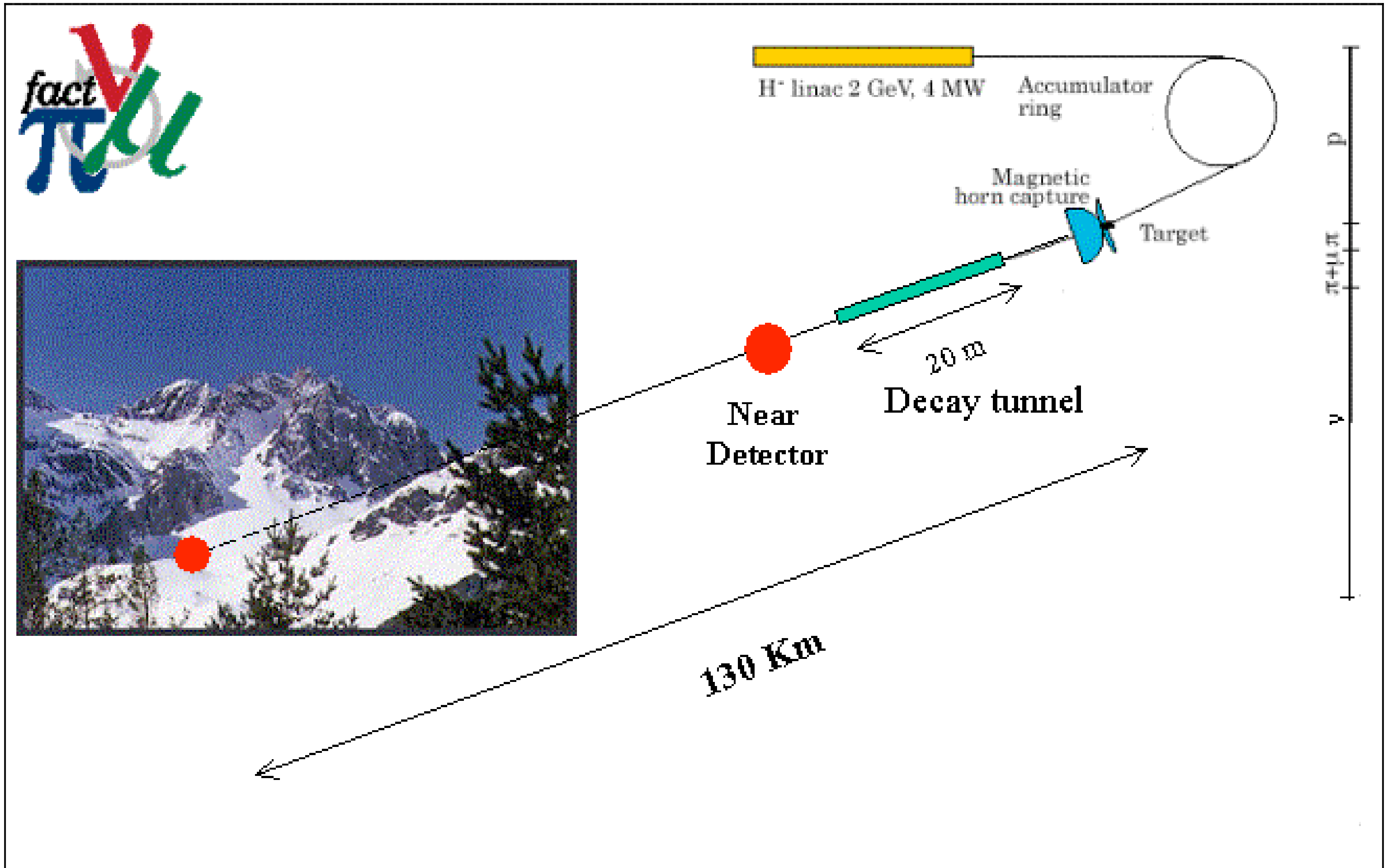
Limits for neutrino + anti-neutrino run

Regular hierarchy ν and Antiν running

Regular hierarchy ν and Antiν running

Sensitivity of Neutrino and Anti-neutrino Running

neutrino 5 years
anti-neutrino 5 years
90% CL.



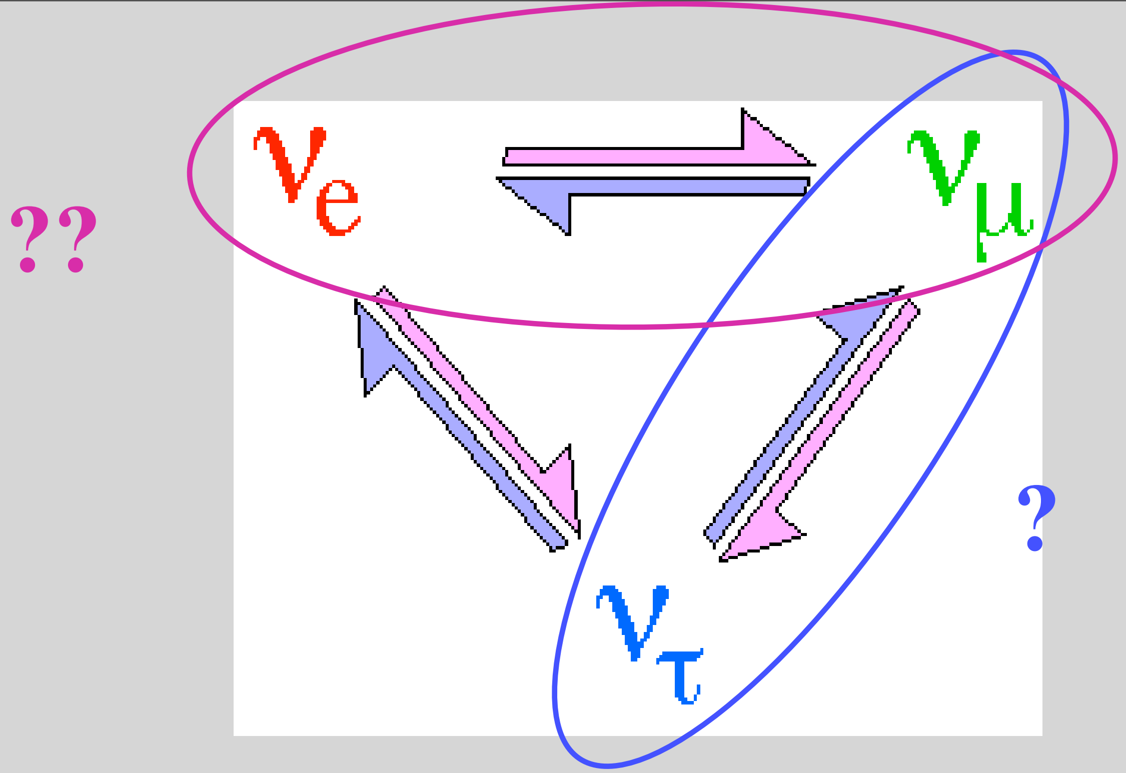
A possible layout of a Low Energy Neutrino Super Beam

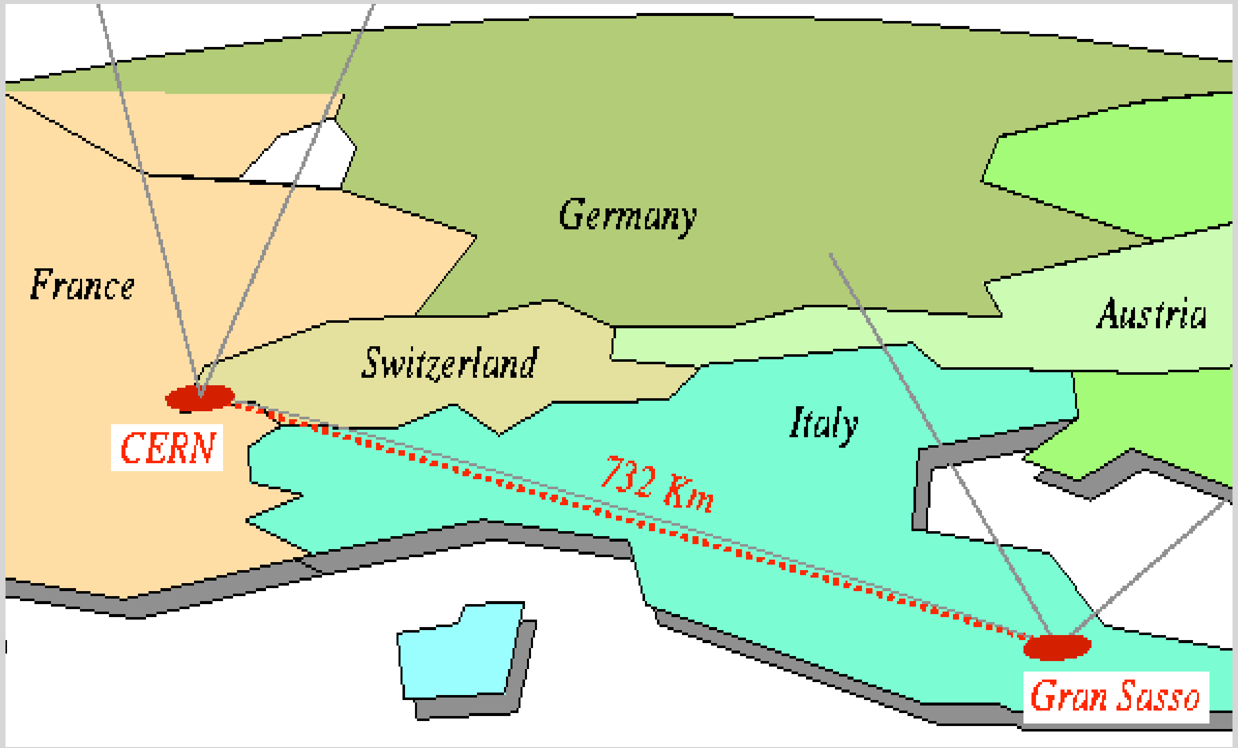
Superbeams in Europe

CNGS (OPERA)
CNGS(ICARUS) not mentioned
SPL-Frejus

CNGS - OPERA and ICARUS

- Search for $\nu_\mu \rightarrow \nu_\tau$ appearance neutrino oscillation
- High energy neutrino beam
  - energy more than tau production threshold
- Long baseline
  - 732 km
- Detection of tau leptons
  - sensitivity $\Delta m^2_{32} = (1.9 - 3.0) \times 10^{-3} eV^2$
  - high background rejection
  - detector mass 0(1 kton)
- As a byproduct, modest search for $\nu_\mu \rightarrow \nu_e$ appearance neutrino oscillation



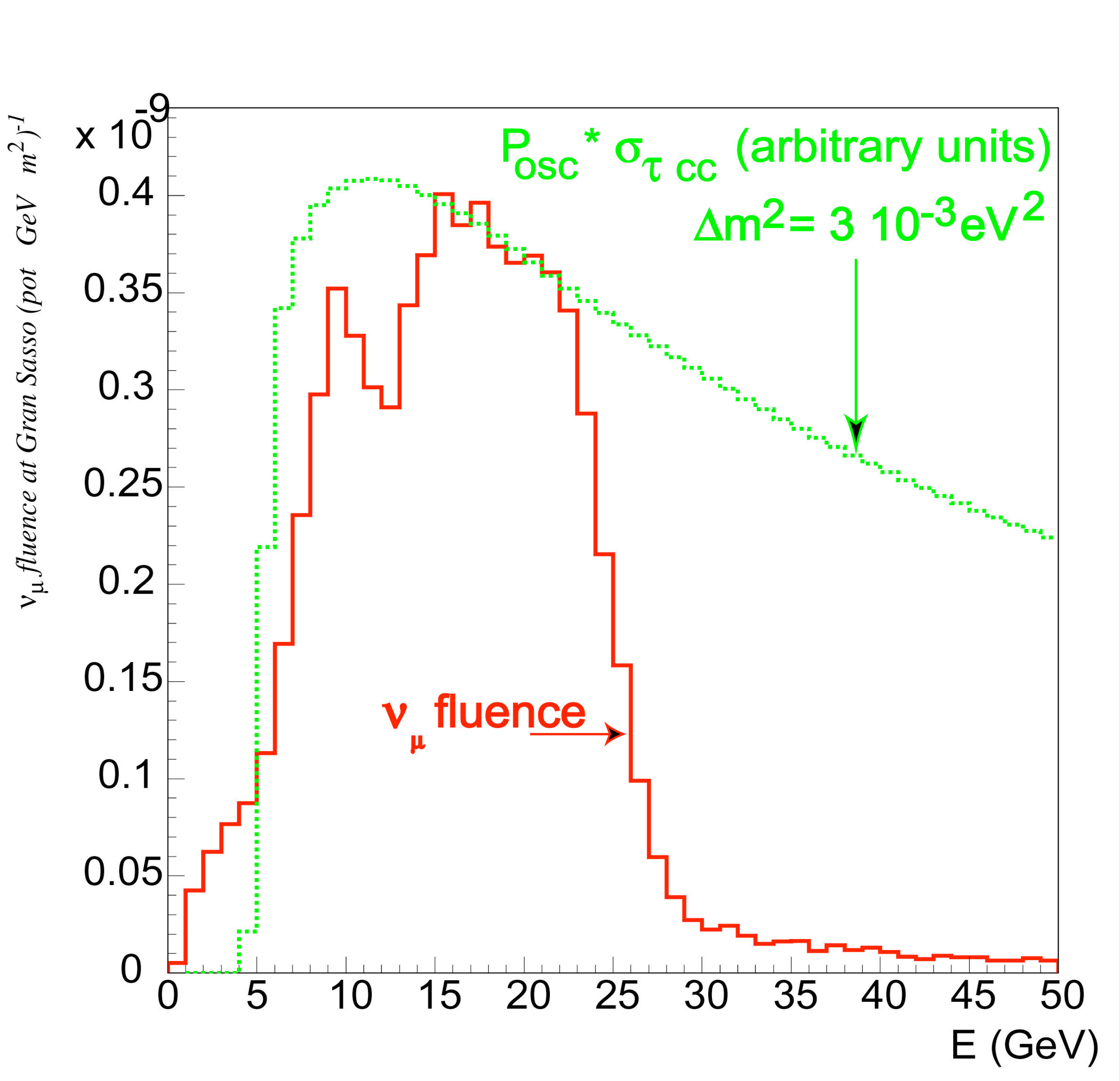


CNGS Beam

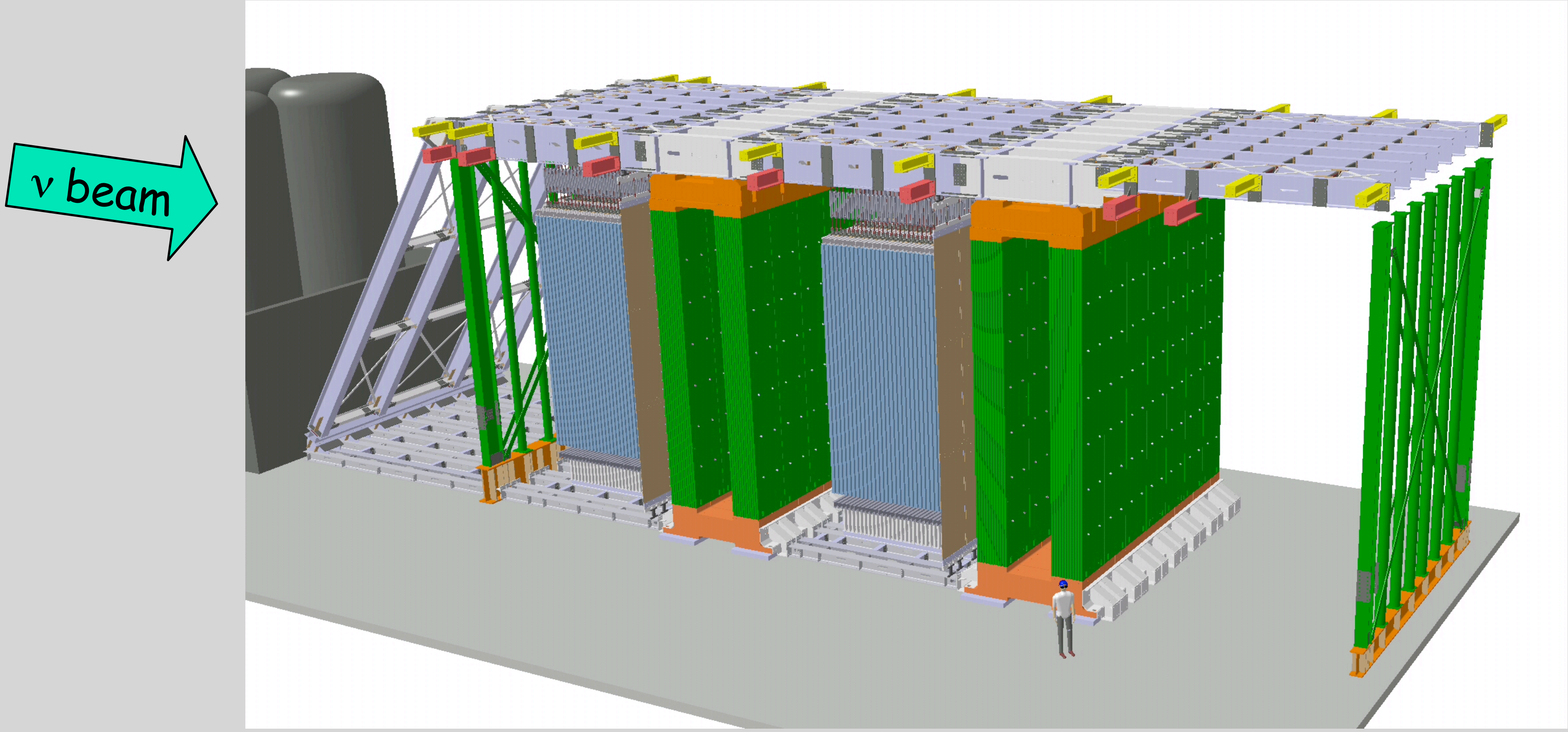
- Optimized for tau appearance
- For 1 year of CNGS, 4.5E19 proton on target/year
- average neutrino energy ~ 17 GeV
- CC events ~ 2900 /kton
- NC events ~ 875 / kton

$$\frac{(\nu_e + \bar{\nu}_e)}{\nu_\mu} < 0.85\%$$

$$\frac{\bar{\nu}_\mu}{\nu_\mu} < 2.1\%$$



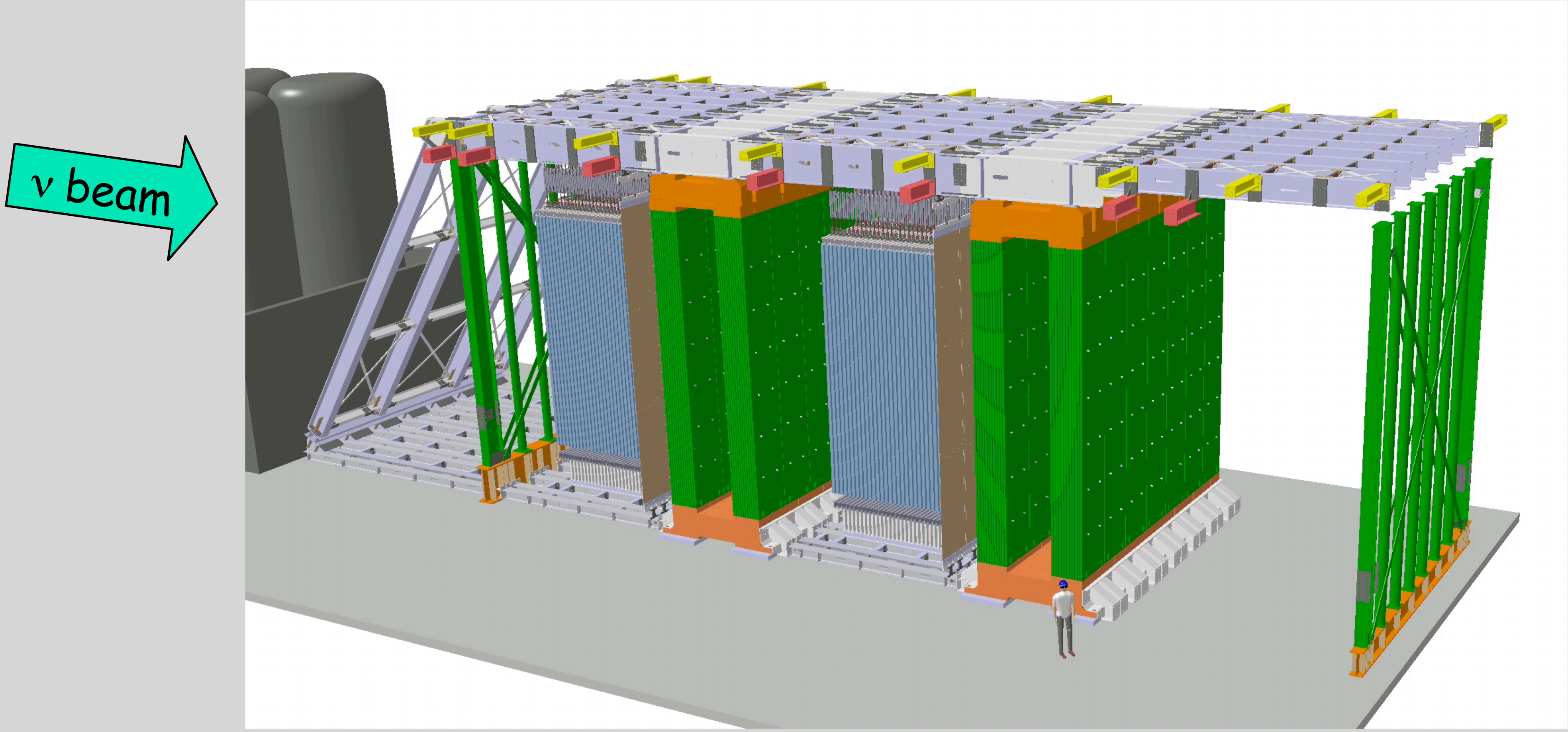
For Δm^2=2.4x10^{-3} and maximal mixing expect 16 ν_τ CC/kton/year at Gran Sasso



Hybrid Detector:

- Two supermodules – Target Mass 1766 tons
- 2 Magnetic spectrometers with RPC & Drift tubes
- 2 x [31 Target Tracker and Target Walls]
- 206,336 “ECC bricks” (56 Pb/Emulsion layers)
- 12 M Emulsion plates (thin double-coated)

Opera Detector



Hybrid Detector:

- Two supermodules – Target Mass 1766 tons
- 2 Magnetic spectrometers with RPC & Drift tubes
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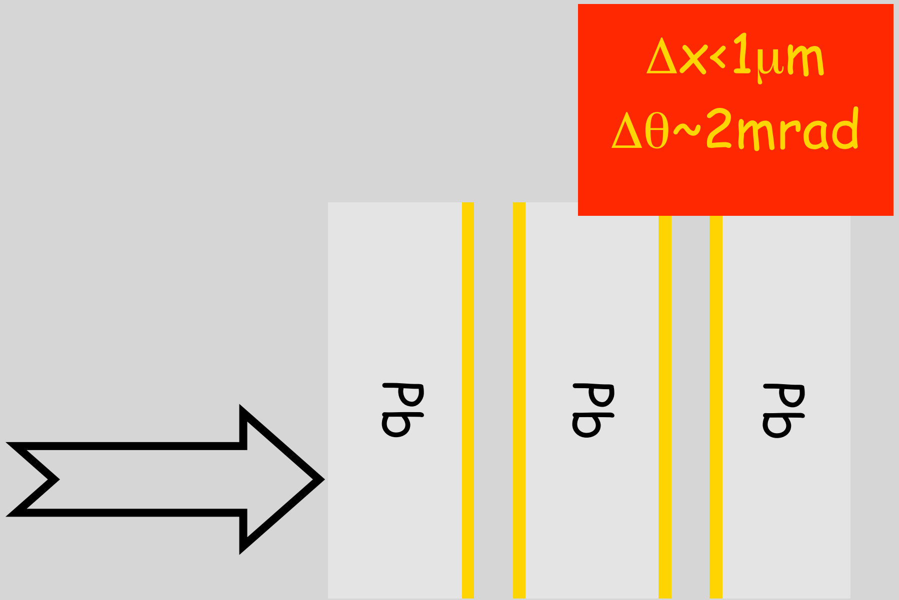
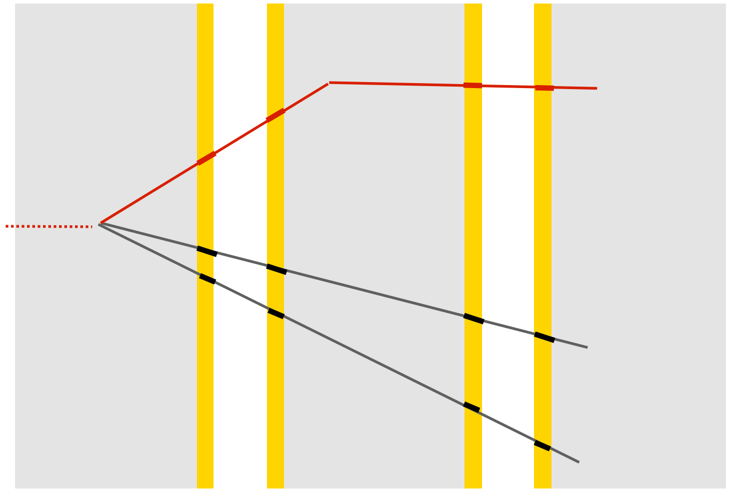

$\Delta x < 1\mu m$

$\Delta\theta \sim 2 mrad$

Opera Detector

$\nu_\mu \rightarrow \nu_\tau$ Search with Emulsions

$\tau \rightarrow$ **e** “ long decays ”
$\tau \rightarrow \mu$ “ long decays ”
$\tau \rightarrow$ **h** “ long decays ”
ε.BR = 2.8-3.5%

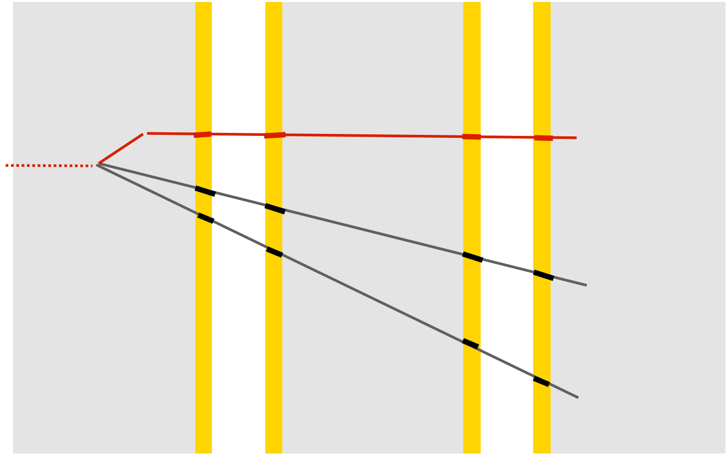


kink angle
$\theta_{kink} > 20$ mrad

Fiducial volume

$\tau \rightarrow$ **e** “ short decays ”
$\tau \rightarrow \mu$ “ short decays ”

ε.BR = 0.7-1%



impact parameter
I.P. > 5 to 20 μm

Recently added: $\tau \rightarrow$ **3h long and short decays**

Main backgrounds:

- charm decays
- large angle μ scattering
- hadron re-interactions

OPERA $\nu_\mu \longrightarrow \nu_\tau$ Signal and Background Rates

full mixing, 5 years run @ 4.5 x10^{19} pot / year

	signal (Δm^2=1.9x10^{-3}eV^2)	signal (Δm^2=2.4 x10^{-3}eV^2)	signal (Δm^2=3.0x10^{-3}eV^2)	BKGD
OPERA 1.8 kton fiducial	6.6	10.5	16.4	0.7
+ brick finding + 3 prong decay	8.0	12.8	19.9	1.0
Background reduction	8.0	12.8	19.9	0.8

OPERA $\nu_\mu \longrightarrow \nu_\tau$ Signal and Background Rates

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	signal ($\Delta m^2=1.9\times10^{-3}eV^2$)	signal ($\Delta m^2=2.4\times10^{-3}eV^2$)	signal ($\Delta m^2=3.0\times10^{-3}eV^2$)	BKGD
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+ brick finding + 3 prong decay	8.0	12.8	19.9	1.0
Background reduction	8.0	12.8	19.9	0.8

1. Charm background :
   - πμ id by dE/dx would reduce this background by 40% (but charm cross-section maybe is higher)

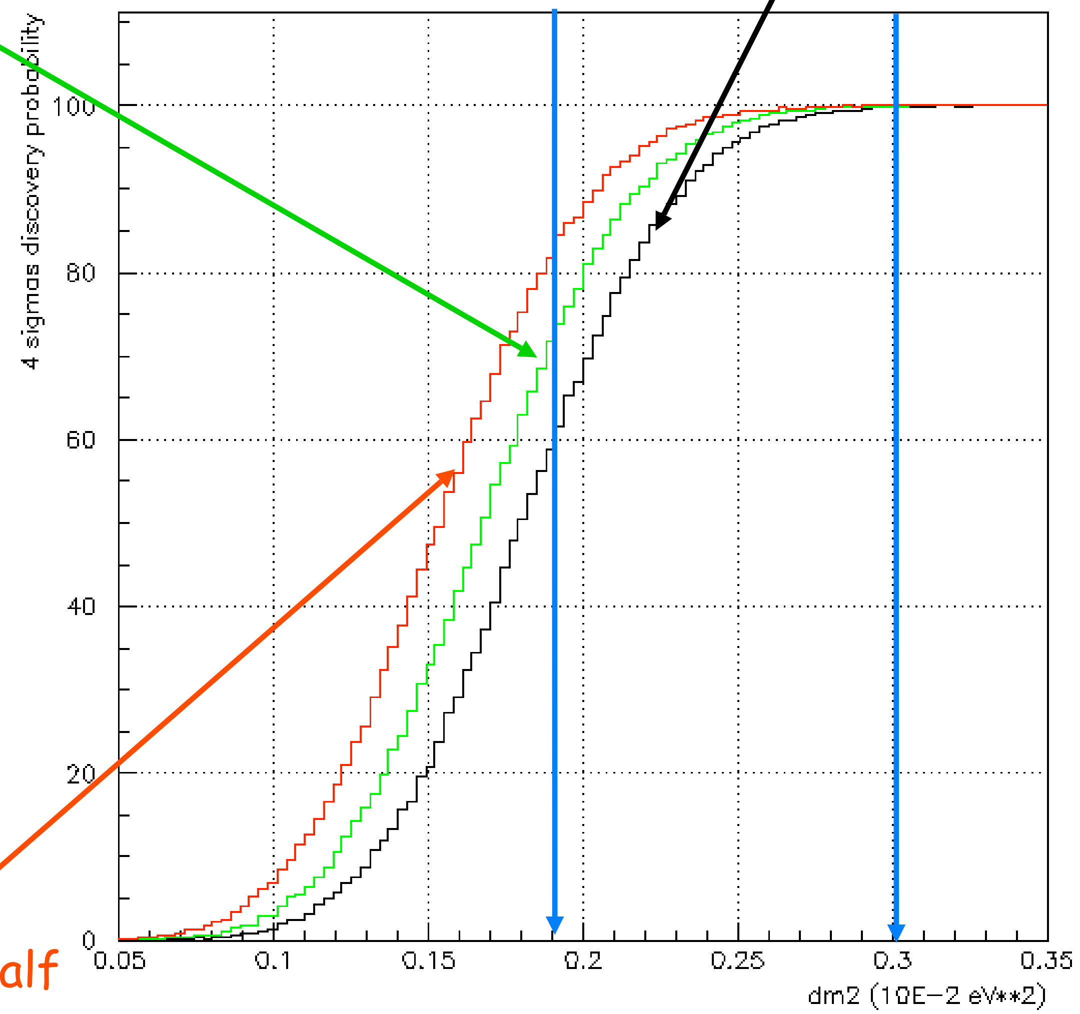
     ⇒ tested at KEK and at PSI (pure beam of π or μ stop): analysis in progress
2. Large angle μ scattering :
   - Upper limit from past measurements used so far
   - Calculations including nuclear form factors give a factor 5 less

     ⇒ test performed at X5 beam with Si detectors: analysis in progress

OPERA $\nu_\mu \longrightarrow \nu_\tau$ Discovery Sensitivity

Opera with expected background improvements -30%

Opera nominal



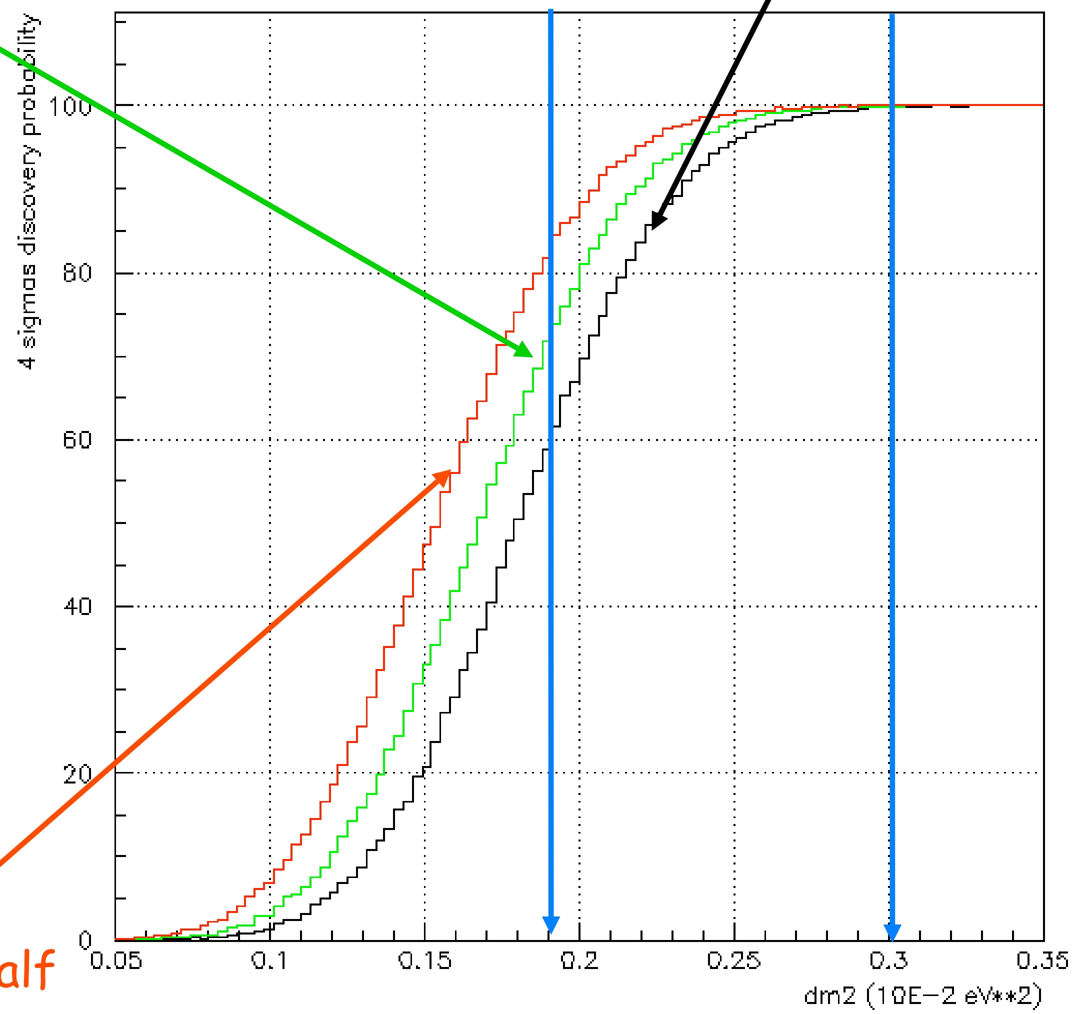
Opera, half background

SK 90% CL (L/E analysis)

OPERA $\nu_\mu \to \nu_\tau$ Discovery Sensitivity

Opera with expected background improvements -30%

Opera nominal

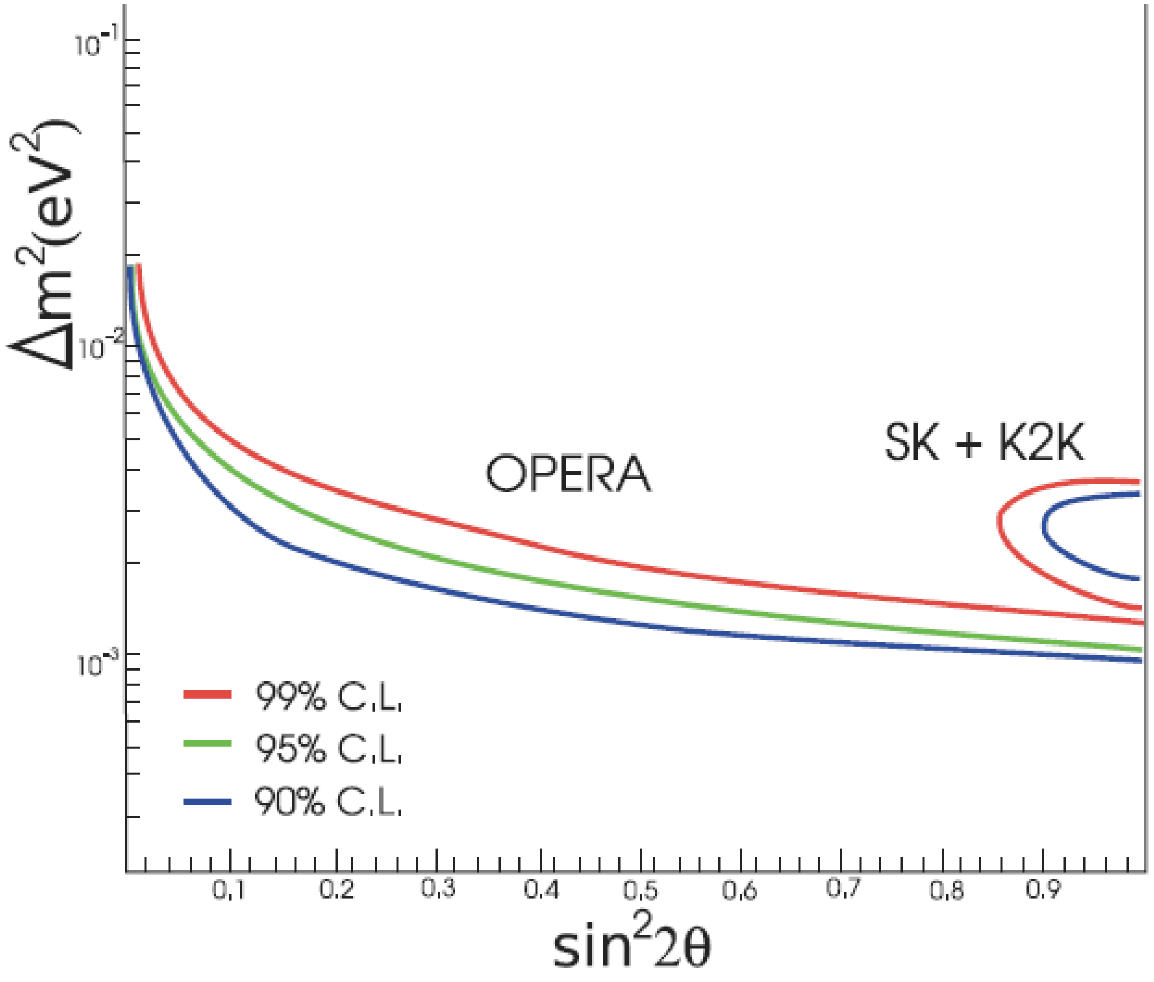


Opera, half background

SK 90% CL (L/E analysis)

4 sigma discovery

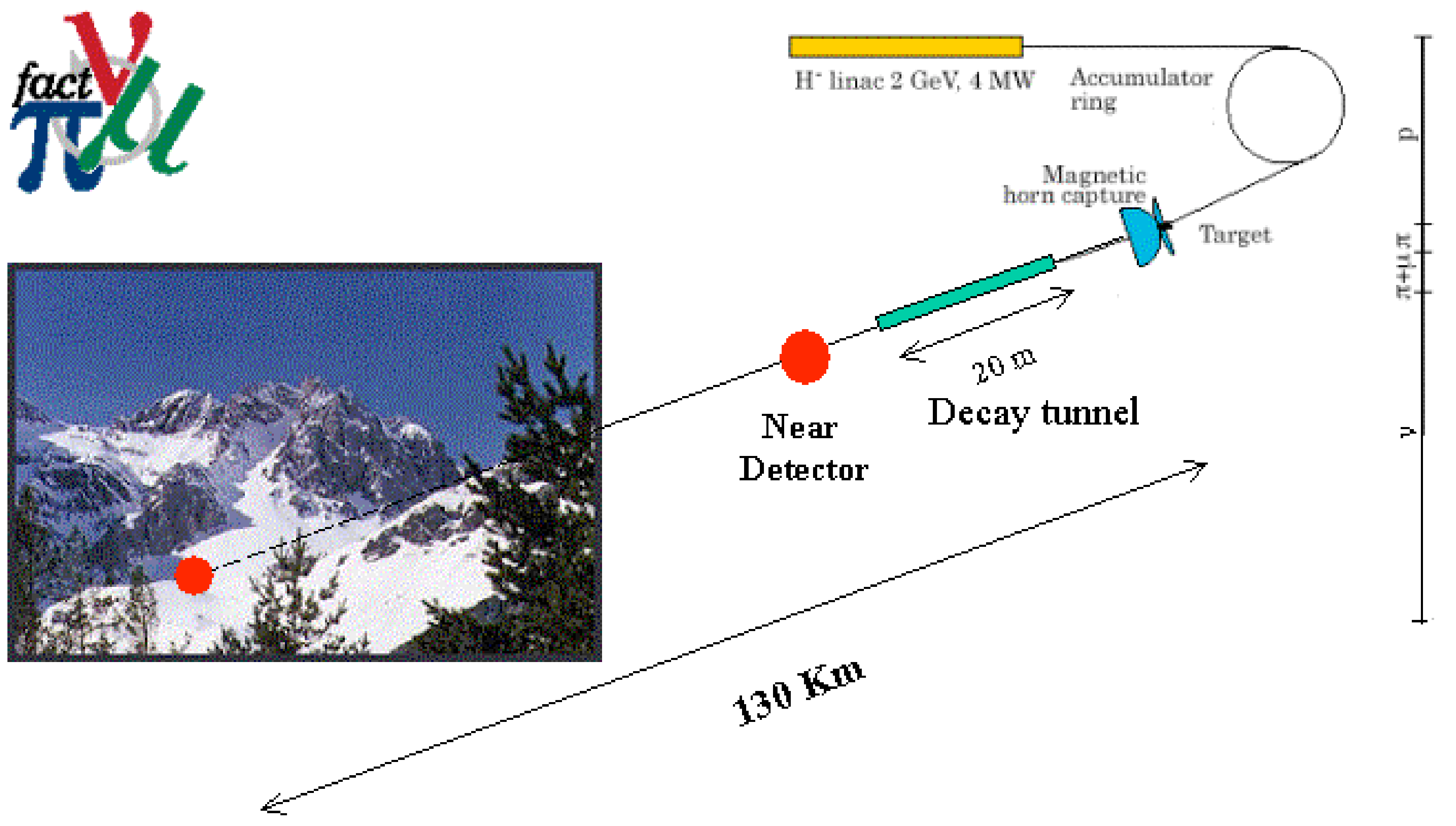
(probability that the observed signal is due to background fluctuation is smaller than 6.3x10-5)



What happens if the tau signal is not seen in OPERA ?

CERN SPL

- SPL (Superconducting Proton Linac at CERN)
  - 2.2 GeV/c proton beam of 4 MWatts



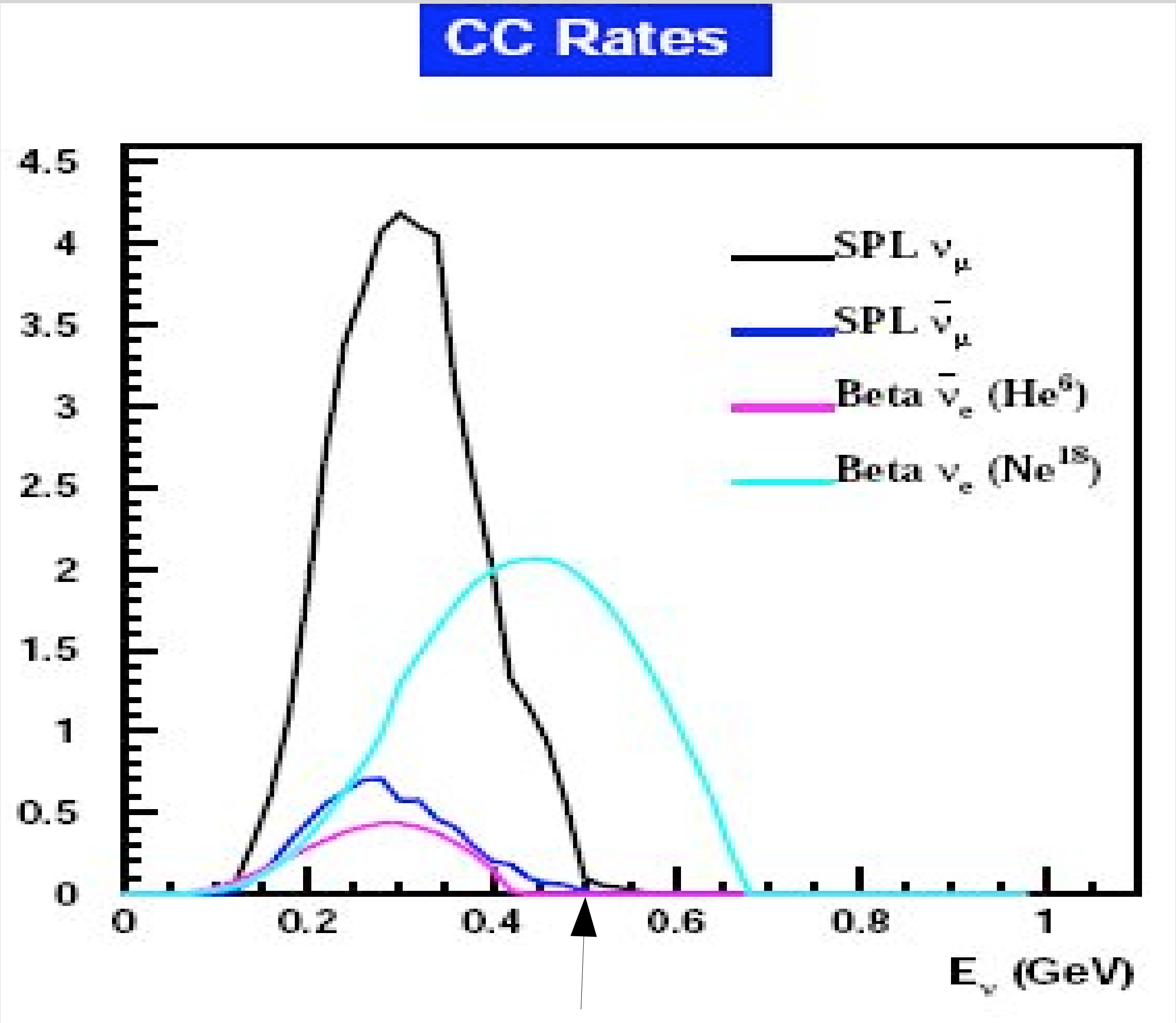
A possible layout of a Low Energy Neutrino Super Beam

Neutrino Spectrum from SPL

- Wide band neutrino beam peaked at near 270 MeV.

- Low proton energy
  - backgrounds from kaon decays are suppressed.

CC events/kton/year



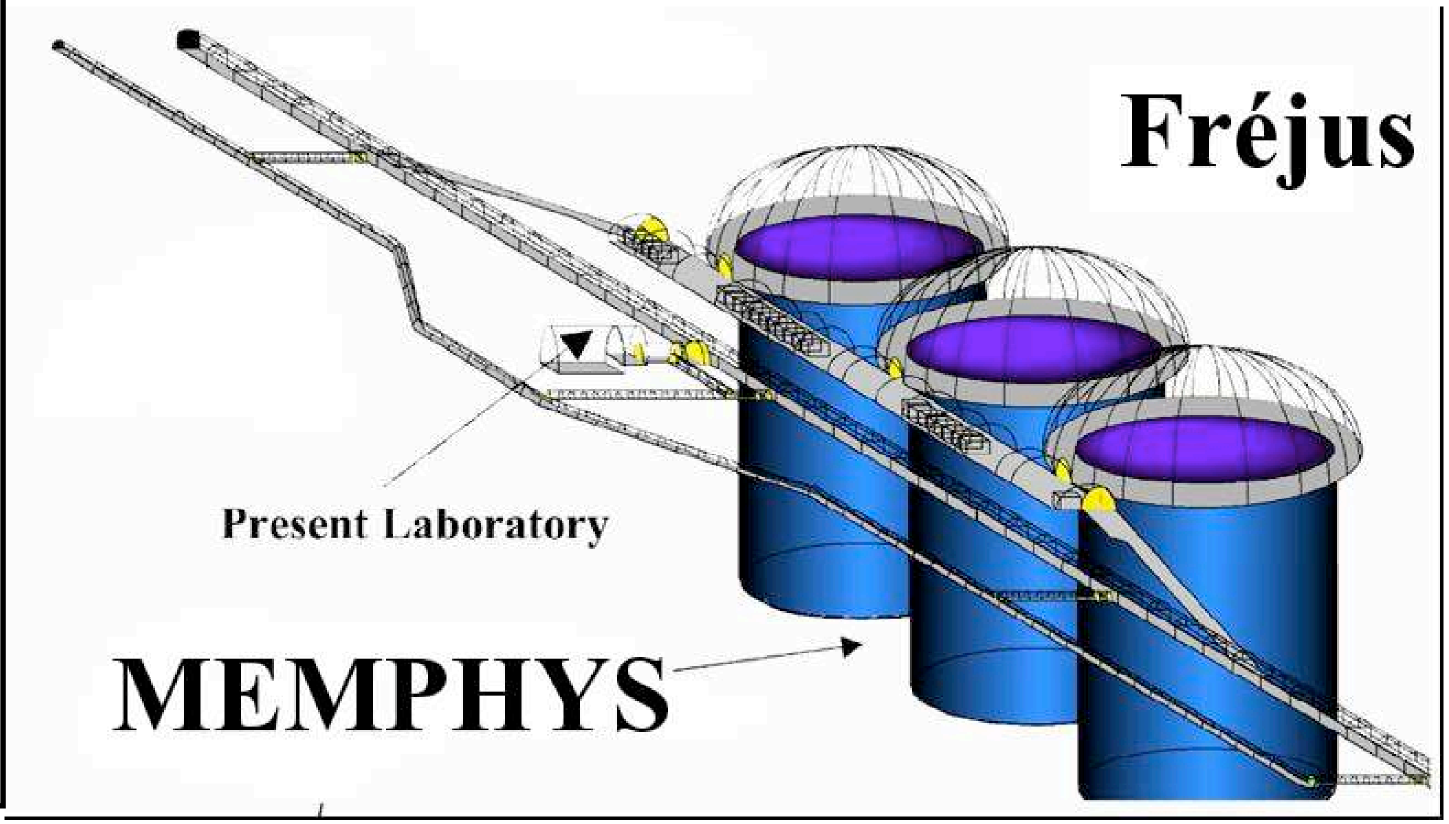
π production threshold

MEMPHYS at Frejus

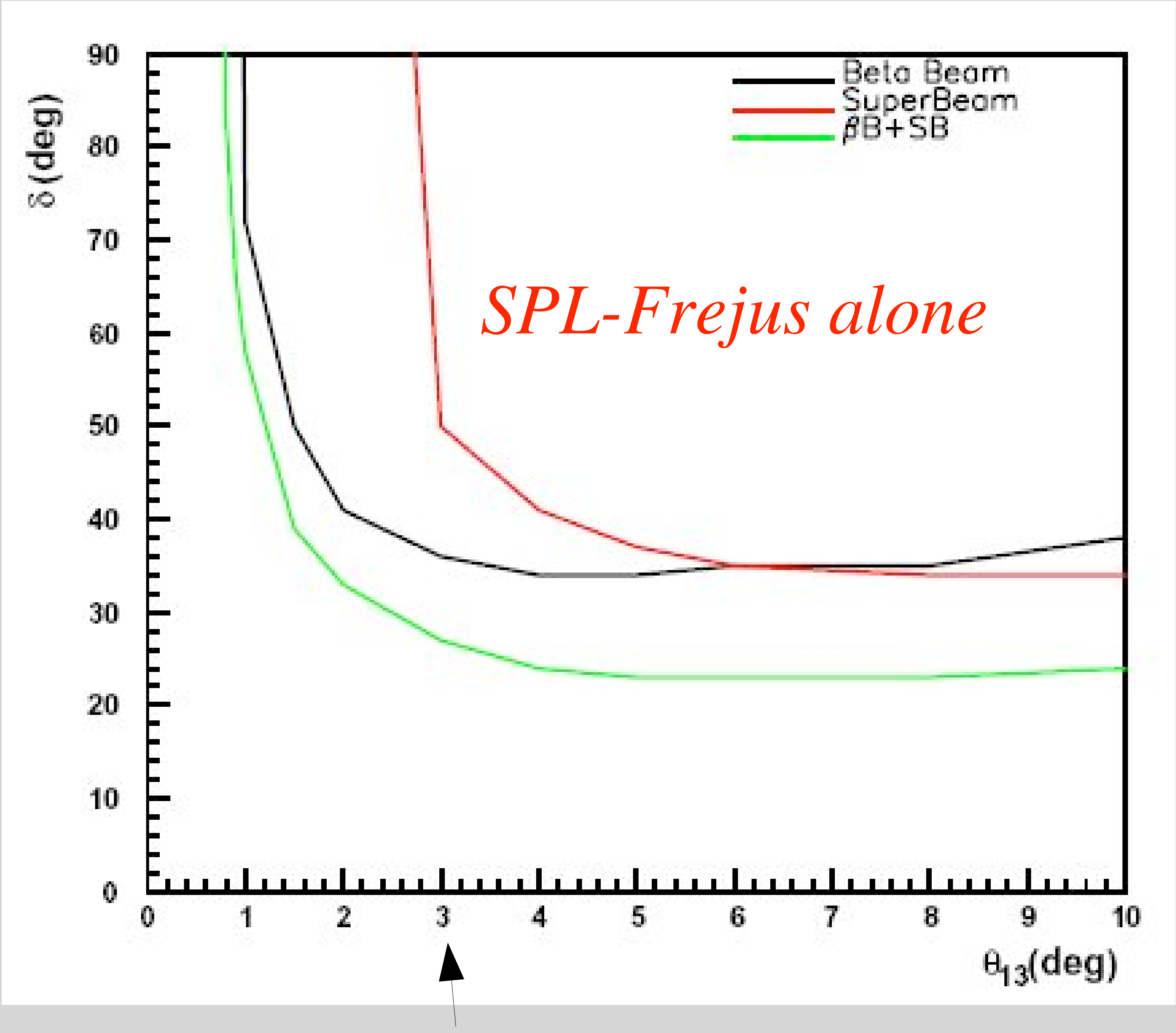
The CERN-MEMPHYS neutrino project

- **Beam**:
  - **βB**: ν_e from ^{18}Ne (5 yr) $+$ $\bar{\nu}_e$ from ^{6}He (5 yr) @ $\gamma = 100$, $\langle E_\nu \rangle = 400$ MeV;
  - **SPL**: 4 MW SPL at CERN, ν_μ (2 yr) $+$ $\bar{\nu}_\mu$ (8 yr), $\langle E_\nu \rangle = 300$ MeV;
- **Baseline**: 130 km (CERN → Fréjus);
- **Detector**: 3×145 Kton water Cerenkov at Fréjus.

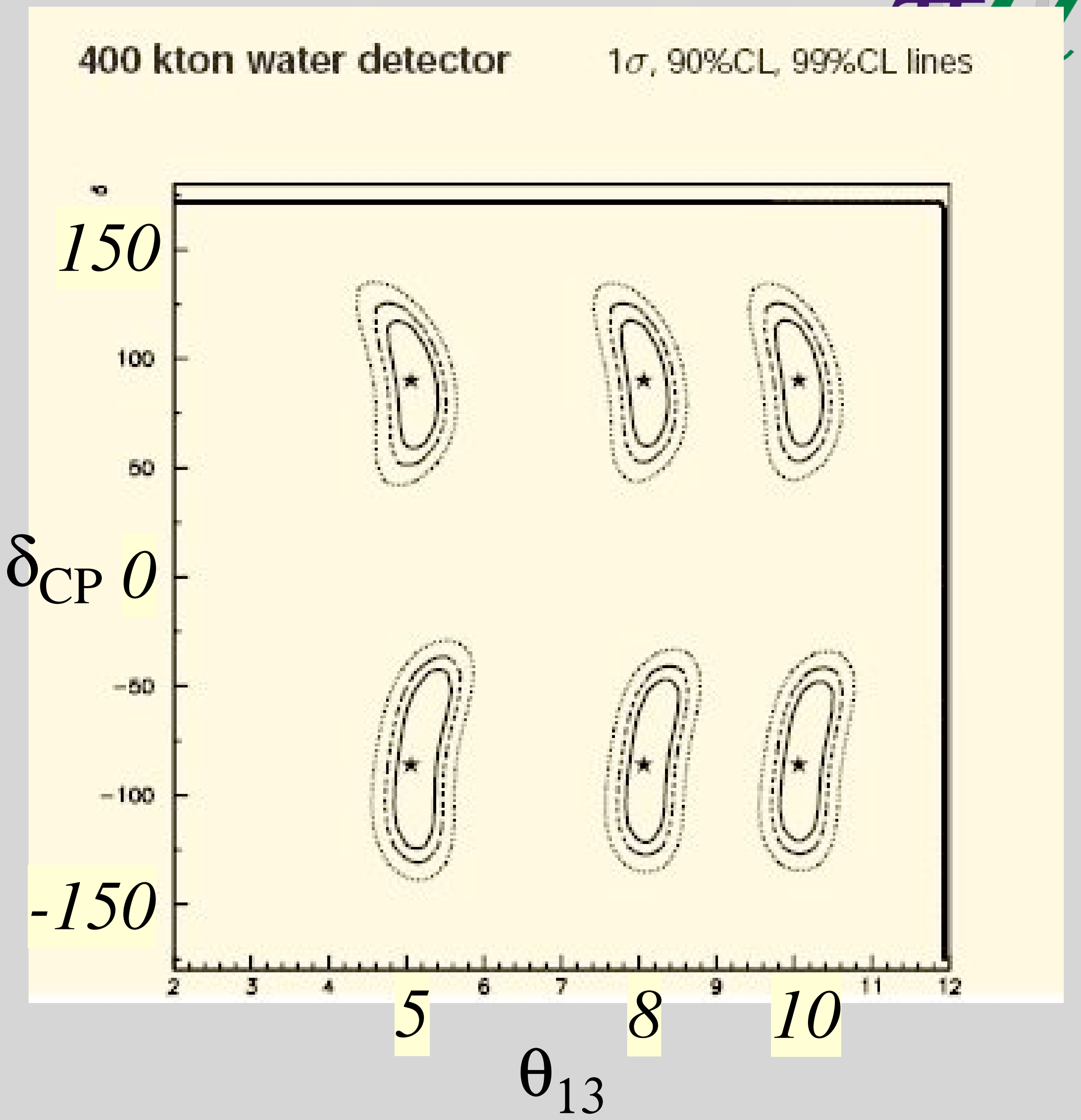
65 m diameter, 65 m height
inner and outer detectors
photodetectors
4800 m w.e.
decision time at 2010
construction of seven years



SPL-Frejus CP Violation Sensitivity



$\sin^2 2\theta_{13} = 0.01$



Exercise 2

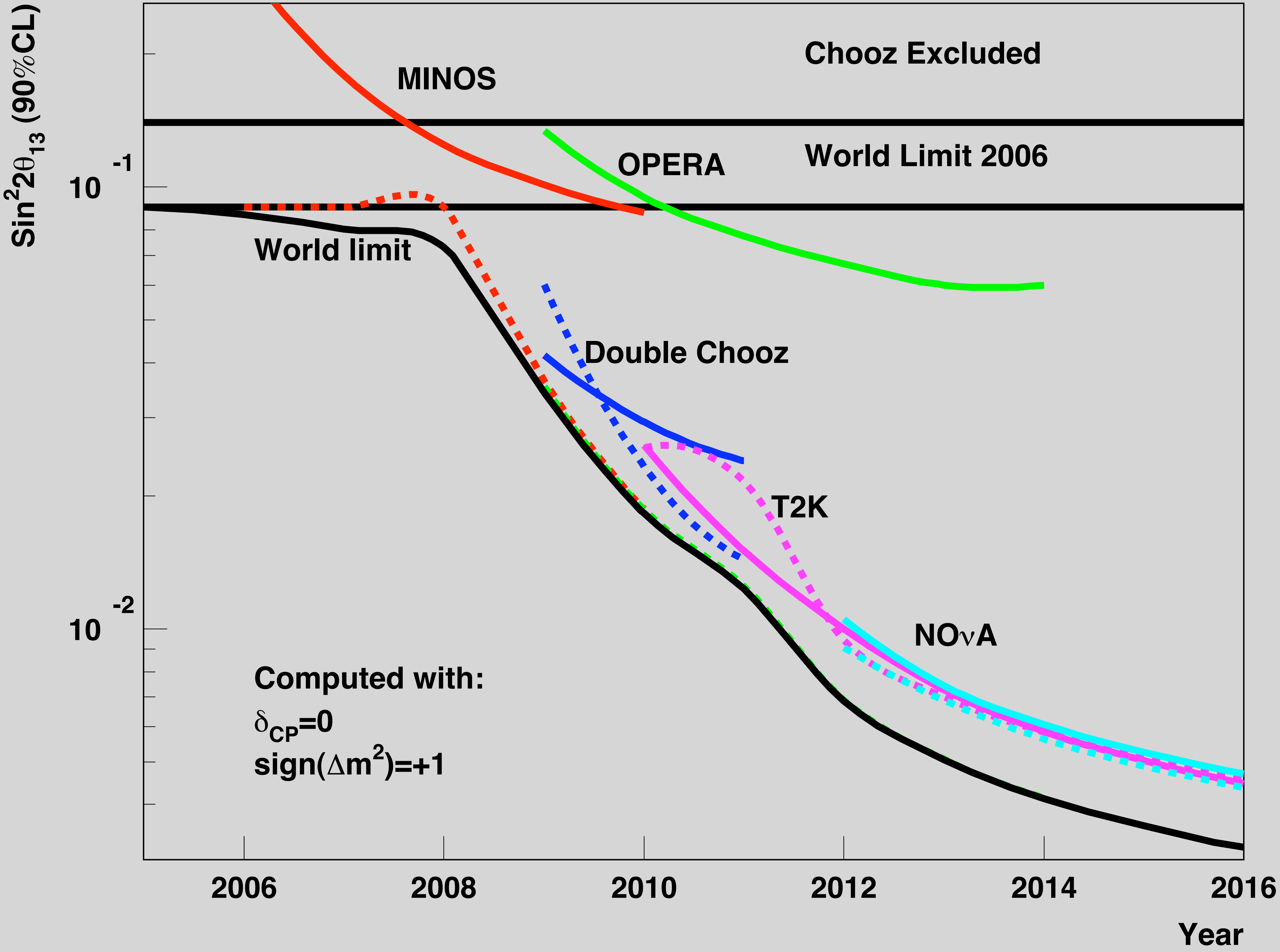
- Show what the minimum tau neutrino energy is for the following the tau production charged current reaction. Confirm that the CNGS beam can produce taus

$$\nu_\tau + n \rightarrow \tau^- + p$$

- For simplicity, use

$$m_p = m_n = 1\mathrm{GeV}/\mathrm{c}^2, m_\tau = 1.8GeV/c^2.$$

hints : Energy and momentum conservation are required. Calculate the center-of-m ass energy.



Upper Limit Sensitivity of $\sin^2 2\theta_{13}$

solid : sensitivity of each exp.
dashed : the world limit without that exp.

Comparison of Superbeams

	Proton Power	Detector (kt)	$\sin^2 2\theta_{13}$	mass hier.	CP
OPERA	0.15 MW	1.8	>0.04		
ICARUS	0.15 MW	2.4	>0.03		
MINOS	0.4 MW	5	>0.05		
T2K	0.75 MW	22.5	>0.006	no	
NOvA	0.4 MW	50	>0.004	ok	
T2HK	4 MW	450	> 0.001	no	>20°
T2KK	4 MW	225+225	>0.001	ok	>20°
SuperNoVA	2 MW	50+50	>0.001	ok	135±20
BNL-DUCEL	1 MW	500	>0.004	ok	40±20
SPL	4 MW	400	>0.002	no	90±30

Summary (First Lecture)

- Goal of future neutrino oscillation physics
  - determination of θ_{13}
  - if $\theta_{13} \neq 0$, search for leptonic CP violation
  - determination of the mass hierarchy.
  - precise determination of Δm^2_{32} and θ_{23}
- Superbeam Experiments (high power protons + large detector)
  - next generation (under preparation) : T2K, NOvA
  - future : T2HK, T2KK, Super NOvA, BNL-Homestake, SPL
- Future direction would be dependent on what we will see from the next generation experiments.