ν '04
June 17, 2004
Paris

Super Beams

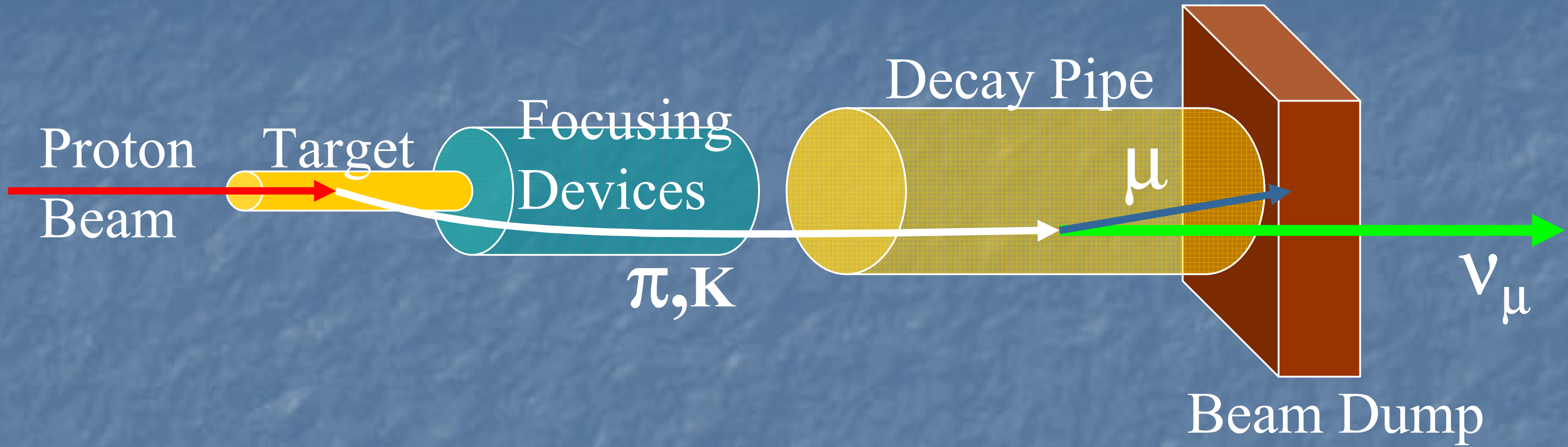
Future dream for 10~20years from now

Takashi Kobayashi

IPNS, KEK

Contents

What is (Original) Super Beam?



Conventional neutrino beam with (Multi-)MW proton beam (←→νFact)

- Pure ν_μ beam (≳99%)
- ν_e (≲1%) from π→μ→e chain and K decay(Ke3)
- $\nu_\mu/\bar{\nu}_\mu$ can be switched by flipping polarity of focusing device

Strongly motivated by high precision LBL ν osc. exp.

Long baseline osc. experiments

Classification by G.Feldman @SB WS@BNL

- 1st phase experiments (Now)
  - Confirmation of atm. ν results
    - K2K(1999~)/MINOS(2005~)/ICARUS/OPERA(2006~)
- 2nd phase experiments (Now~10yrs)
  - **Discovery of ν_e appearance**
  - Designed & Optimized aft. SK atm ν
  - ~MW beam w/ ~50kton detector
    - T2K-I (approved. 2009~)/NOνA (2009?~) / (C2GT)

"Super Beam" Experiments

- 3rd phase experiments(10~20yrs?)
  - **CP violation and mass hierarchy** thru $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ app.
  - Typically Multi-MW beam & Mton detector
  - 2nd phase is critical step to go

$\nu_\mu \rightarrow \nu_e$ appearance & CPV

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \ (1 - 2S_{13}^2)\right)$$ **Main**

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12}C_{23} \cos\delta - S_{12}S_{13}S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$ **CP-odd**

$$+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$ **Solar**

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} (1 - 2S_{13}^2)$$ **Matter**

$\delta \rightarrow -\delta$, $a \rightarrow -a$ for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Matter eff.:

$$a = 7.56 \times 10^{-5} [\text{eV}^2] \cdot \left(\frac{\rho}{[\text{g/cm}^3]}\right) \cdot \left(\frac{E}{[\text{GeV}]}\right)$$

$$A_{CP} \equiv \frac{P - \bar{P}}{P + \bar{P}} \approx \frac{\Delta m_{12}^2 L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin\delta$$

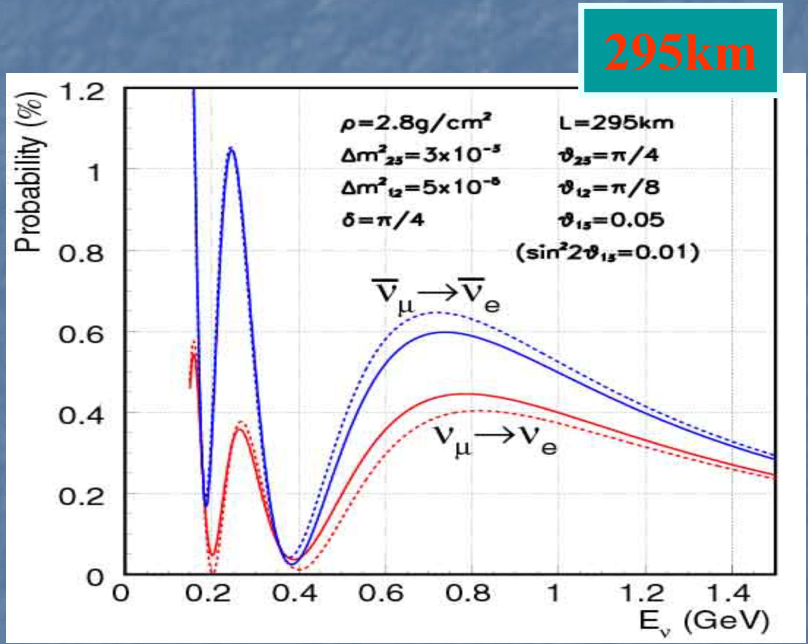
\# of signal $\propto \sin^2\theta_{13}$ (Stat err $\propto \sin\theta_{13}$),
CP-odd term $\propto \sin\theta_{13}$

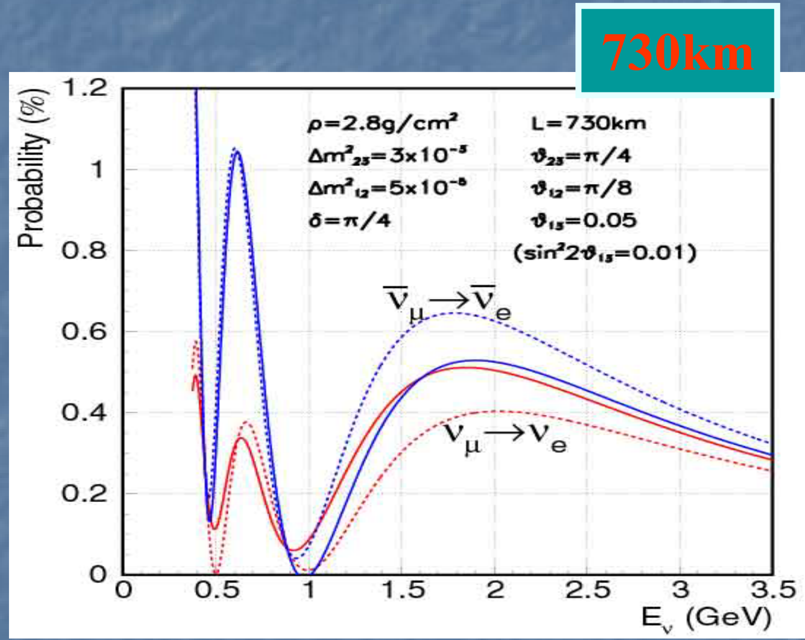
Sensitivity indep. from θ_{13} (if no BG & no syst. err)

CPV vs matter effect

$\nu_\mu \rightarrow \nu_e$ osc. probability w/ CPV/matter

$$P \equiv P(\nu_\mu \rightarrow \nu_e)$$
$$\overline{P} \equiv P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$$



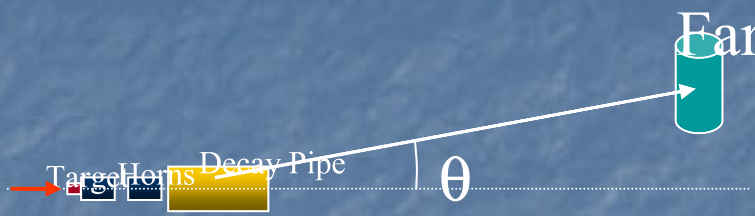


@$\sin^2 2\theta_{13}$=0.01

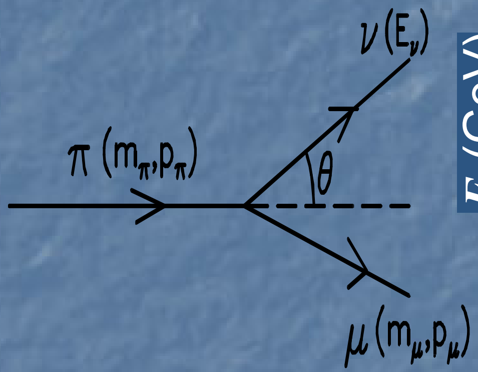
Smaller distance/lower energy → small matter effect
Pure CPV & Less sensitivity on sign of Δm^2
Combination of diff. E&L help to solve.

High intensity narrow band beam
-- Off-axis (OA) beam --

(ref.: BNL-E889 Proposal)

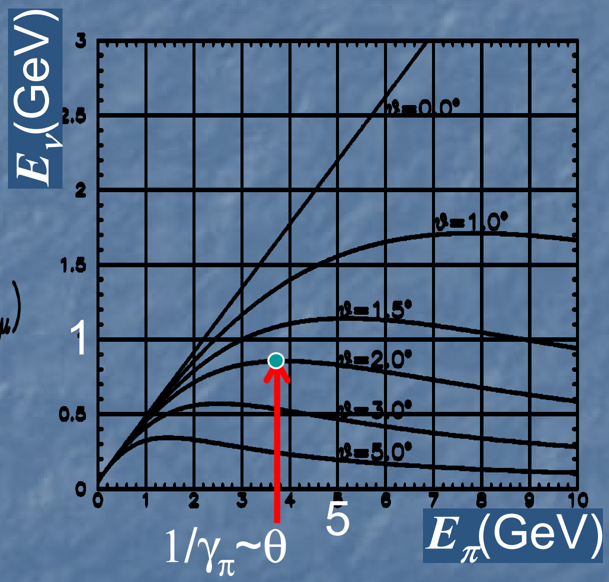


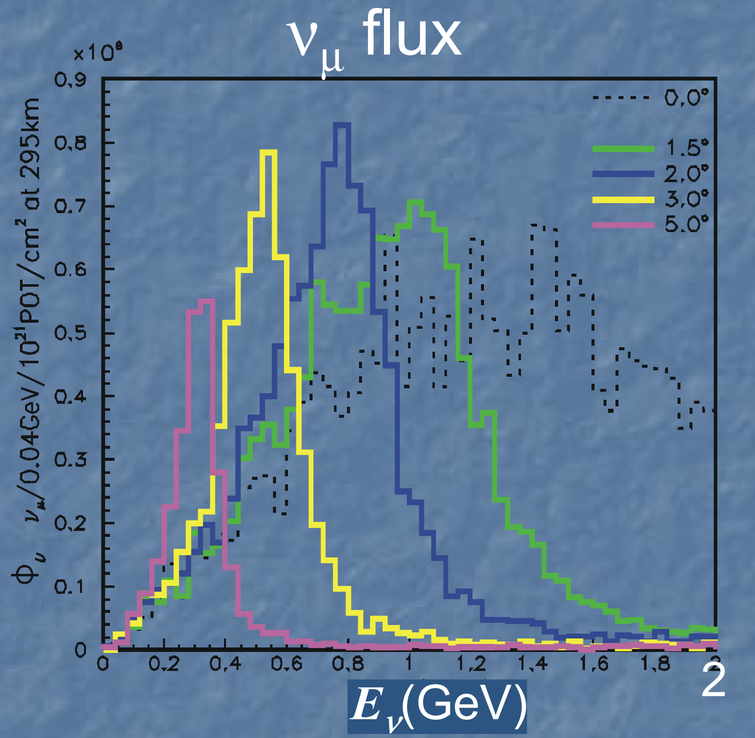
Decay Kinematics



$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$

$$E_\nu^{\max}[\mathrm{GeV}] \approx \frac{30}{\theta[\mathrm{mrad}]}$$

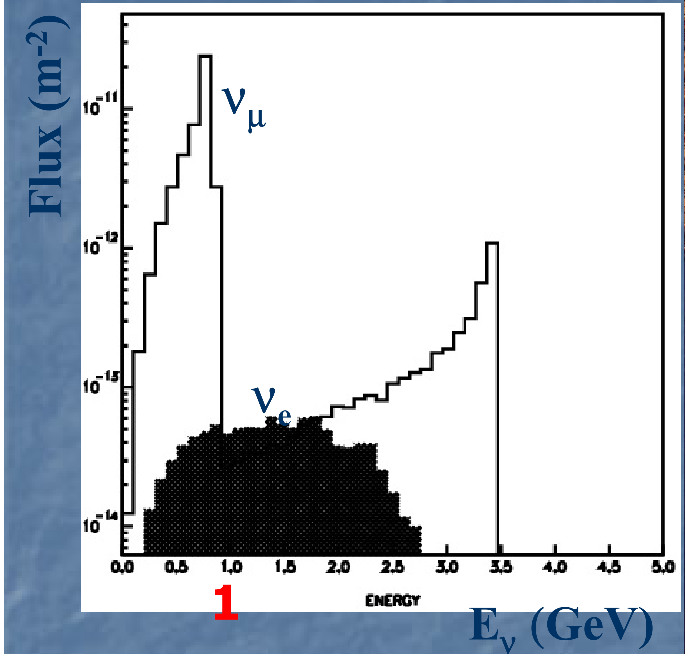


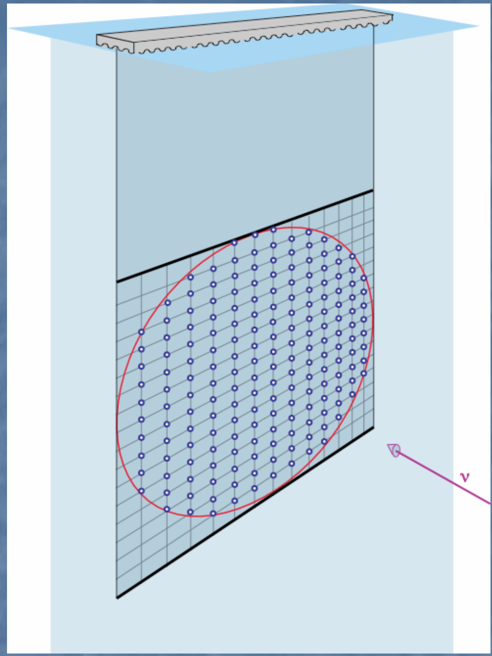


- Increase statistics @ osc. max.
- Decrease background from HE tail

Idea of C2GT (CNGS to Gulf of Taranto)

F.Dydak et.al.

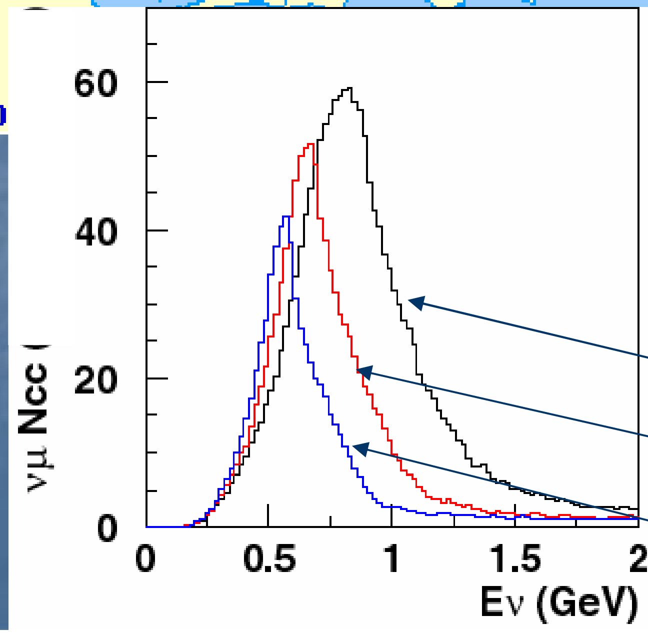




- OA-CNGS
- Movable underwater Cherenkov det. (r=150m), 2Mt fid vol, L=1,200~1,600km
- ~5,000 νμ CC/year
- Disappearance & Appearance
- $\sin^2 2\theta_{13}$~0.008 @90%
- Technology to be established (underwater, light collection, LE PID,…)

T2K-II

- (0.75MW→)4MW 50GeV PS @ J-PARC
- OA 2~3deg
- Eνpeak=0.5~0.8GeV
- L=295km
- Hyper Kamiokande
- ~360k νμ CC/yr
- θ_{13}, CPV
- Small matter effect

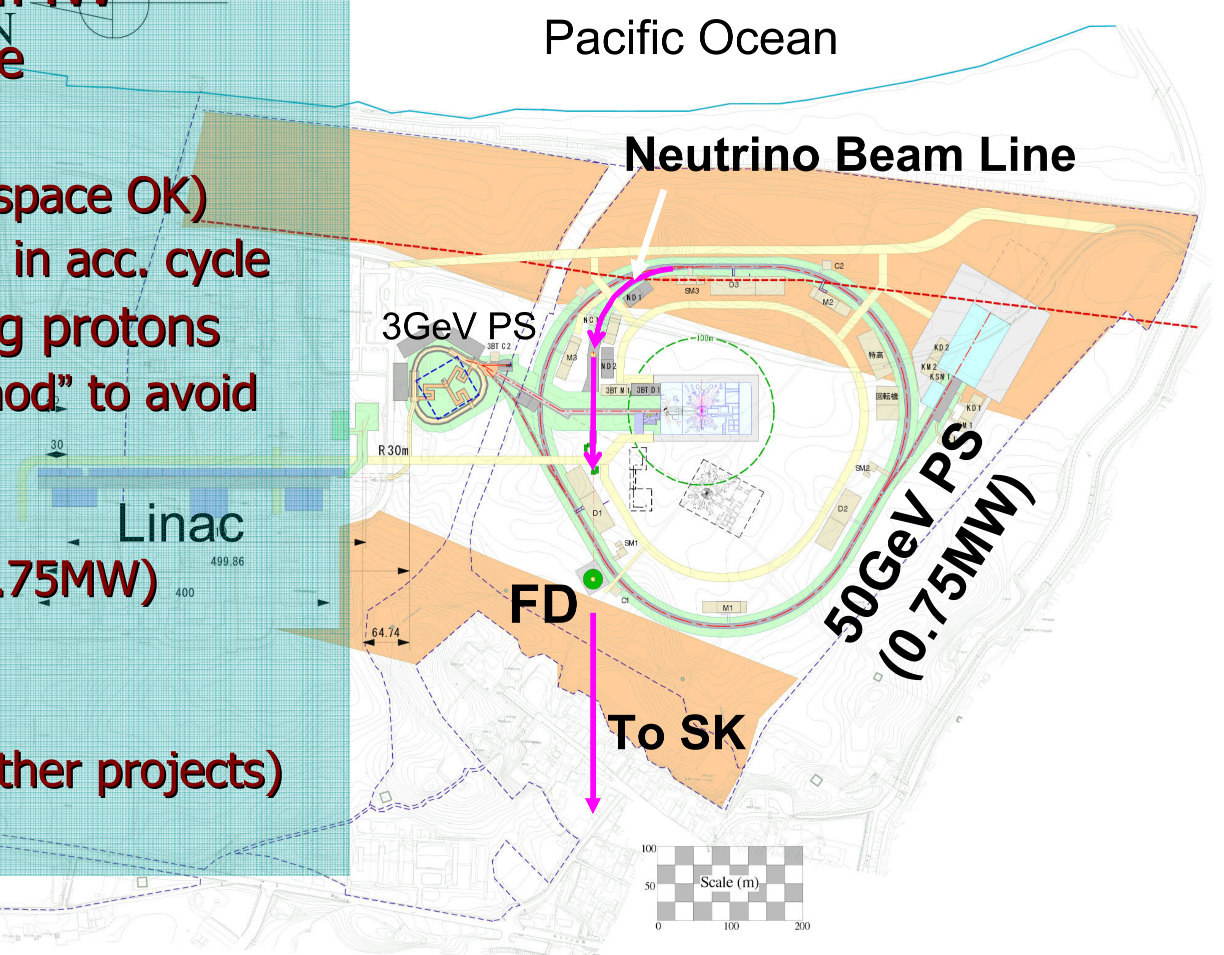


J-PARC
(Japan Proton Accelerator Research Complex)

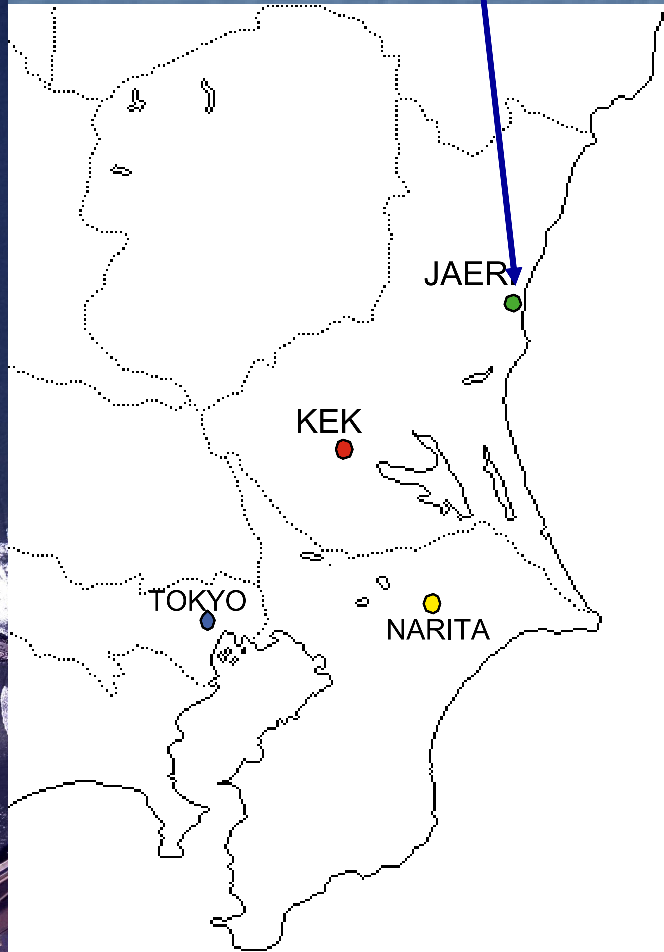
(formerly known as JHF)

- Construction: 2001~2007
- 0.75MW 50GeV-PS
- Possible upgrade to 4MW
  - Preliminary study done
  - Rep. rate x 2.5
    - Double RF cavities (space OK)
    - Eliminate idling time in acc. cycle
  - Double # of circulating protons
    - “barrier bucket method” to avoid space charge limit
  - Issues
    - Achieve first goal (0.75MW)
    - Beam loss
    - Target,…

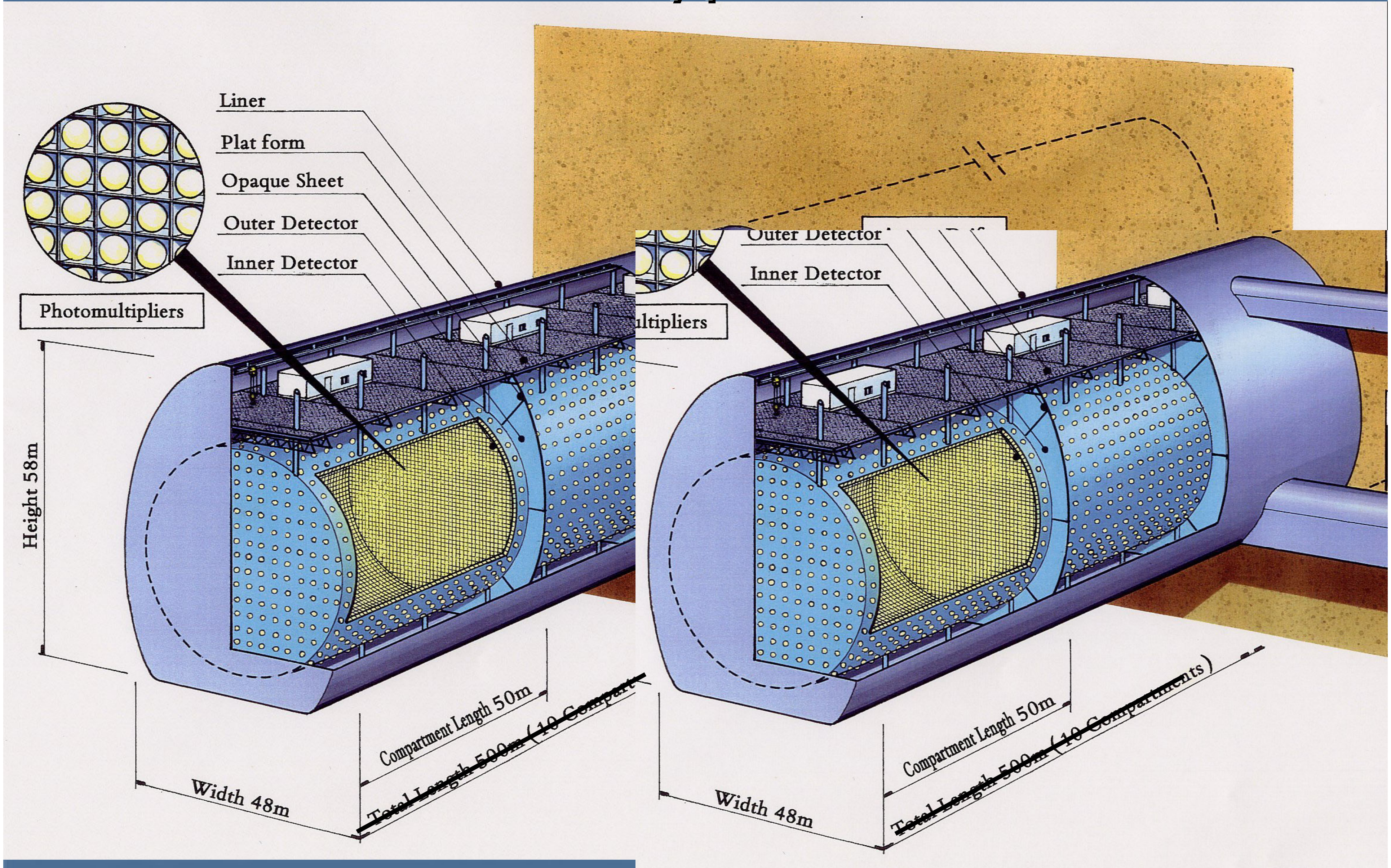
    (these apply also for other projects)



J-PARC

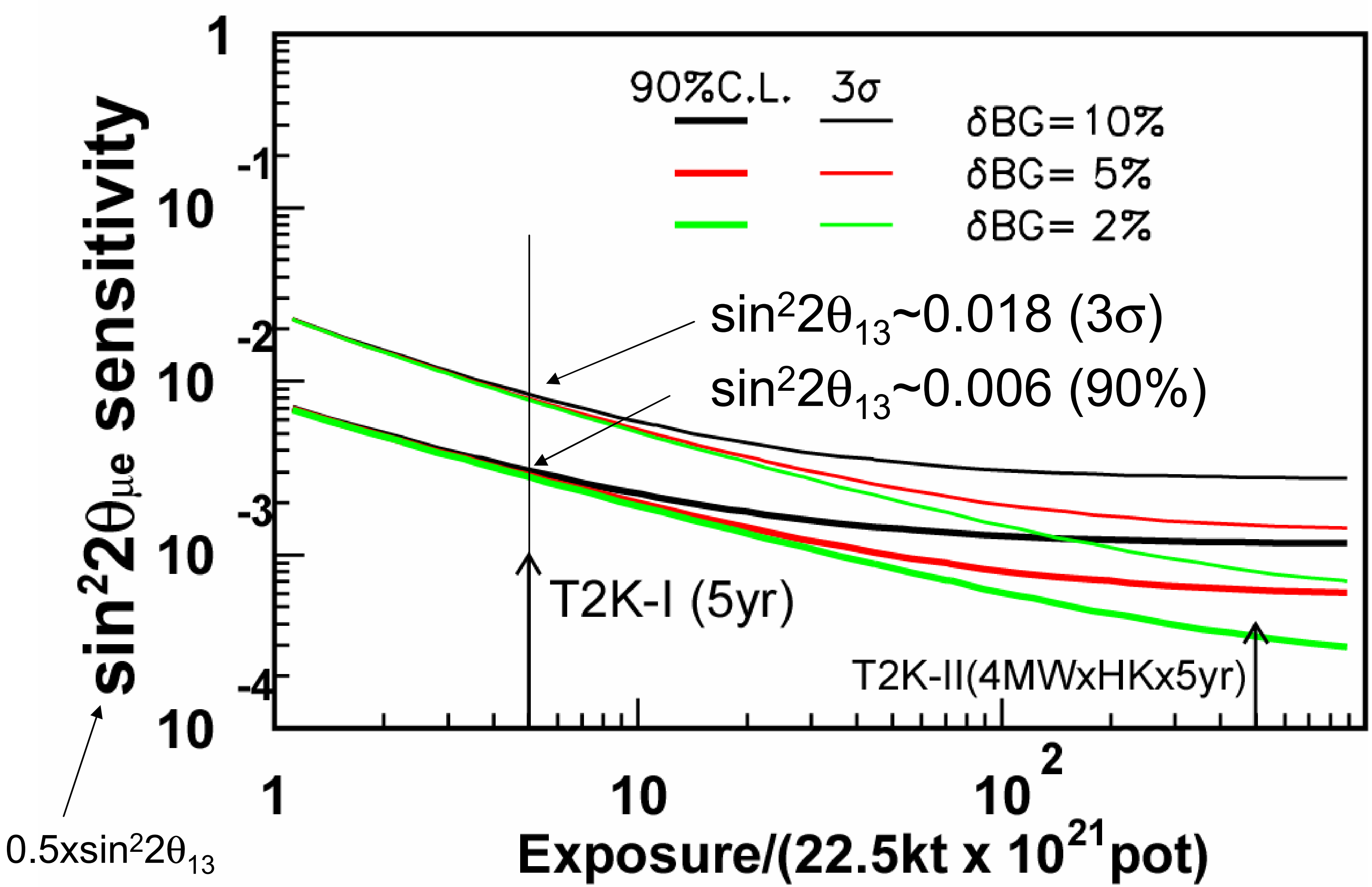


Far Detector: Hyper-Kamiokande



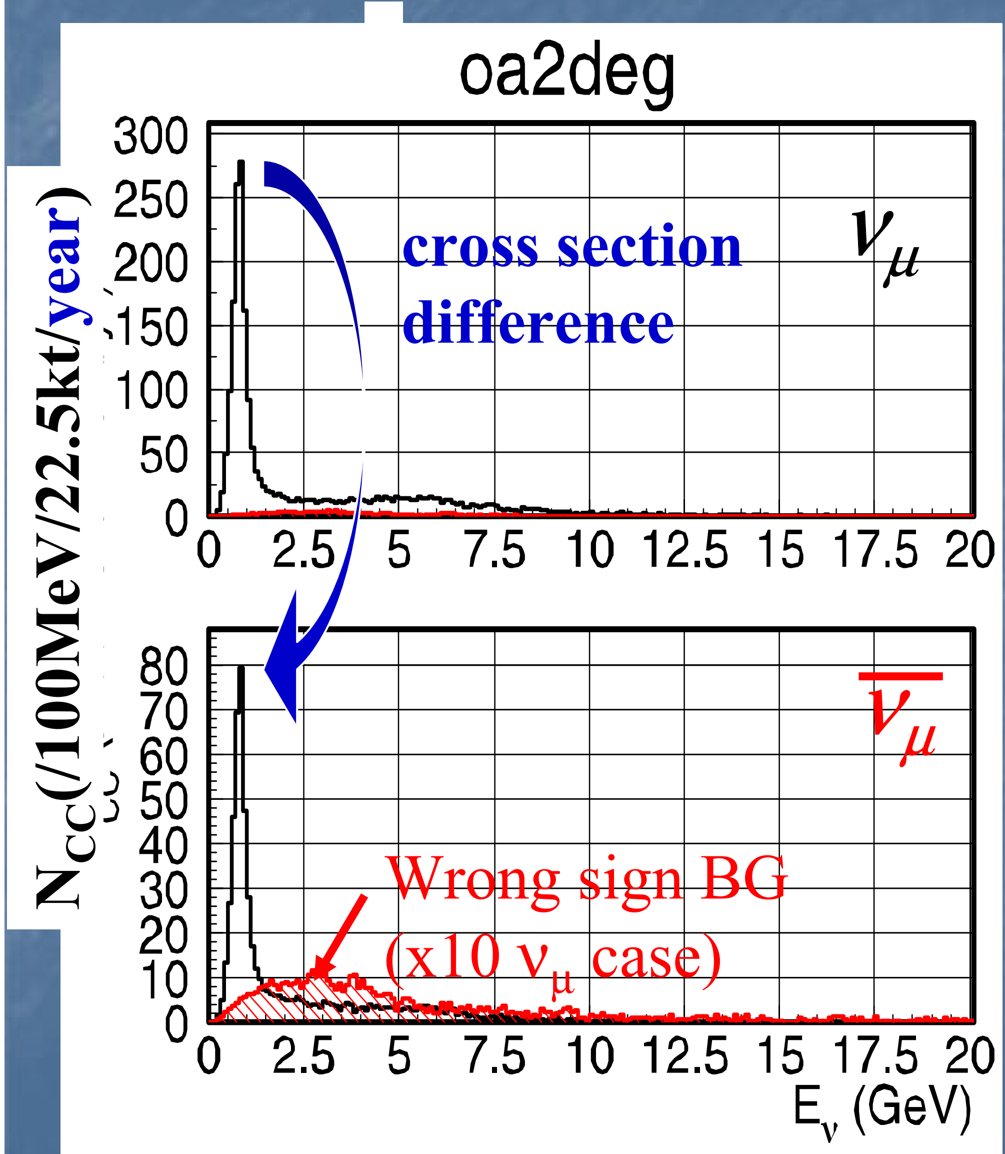
2 detectors × 48m × 50m × 250m, Total mass = 1 Mton

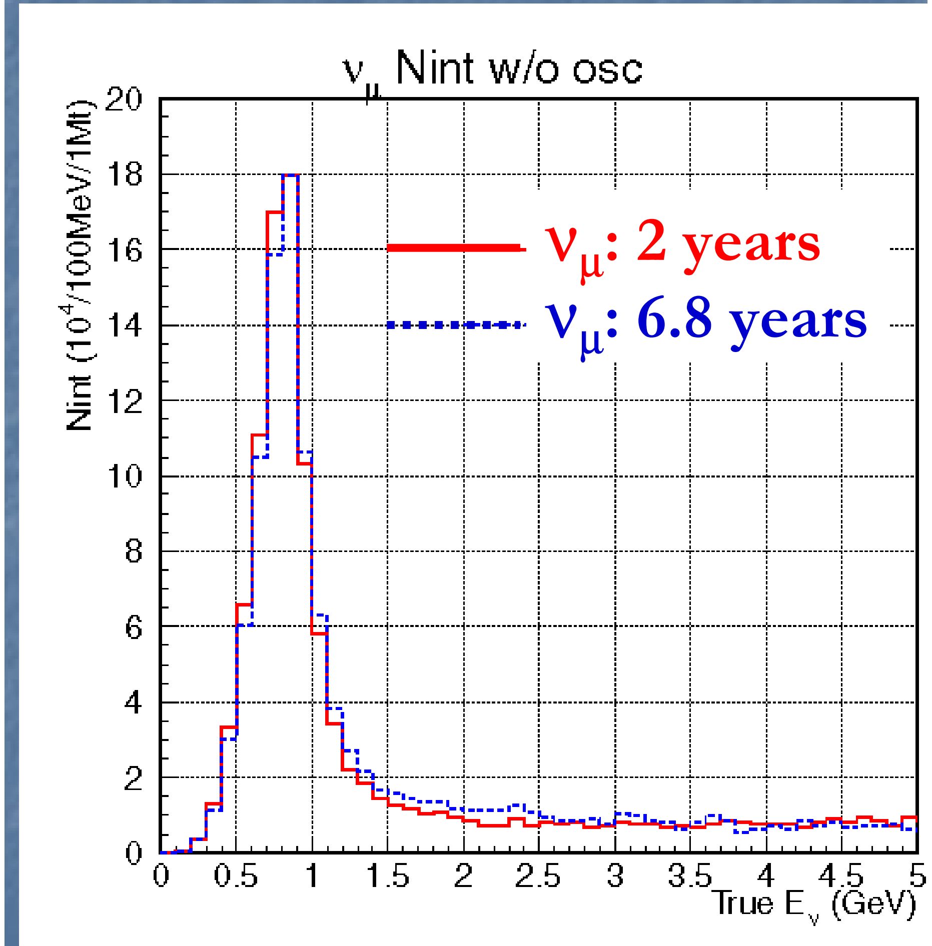
Sensitivity for θ_{13}



$\sin^2 2\theta_{13} < 10^{-3}$ can be searched if syst err ~ few %

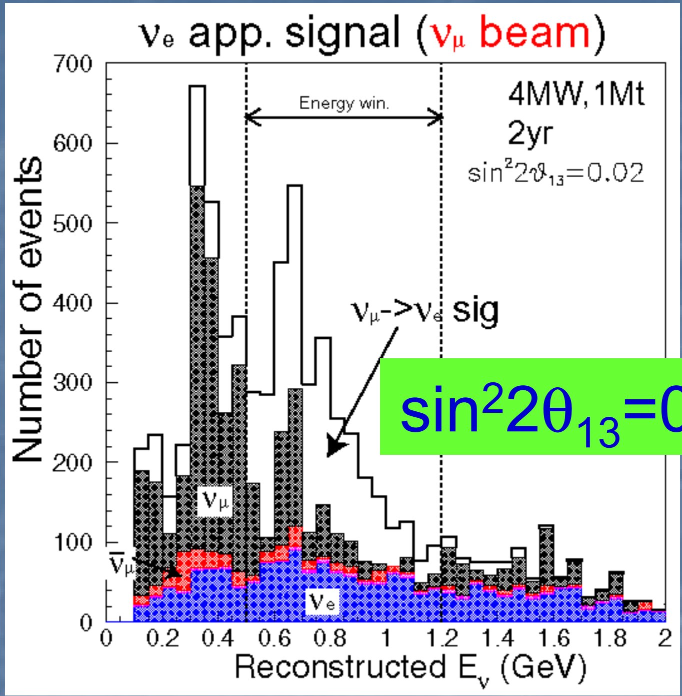
ν / $\bar{\nu}$ CC interaction spectrum for CPV meas.

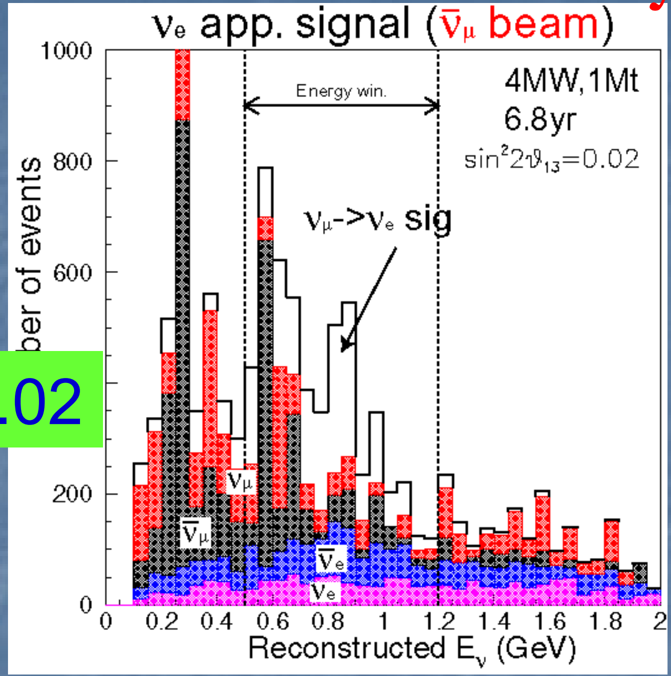




Expected signal and BG (SK full sim)

Very Preliminary





$\sin^2 2\theta_{13}$=0.02

ν_μ:2yr, ν_μ:6.8yr
4MW
0.54Mt

Δm_{21}^2=6.9x10^{-5}eV^2
Δm_{32}^2=2.8x10^{-3}eV^2
θ_{12}=0.594
θ_{23}=π/4
θ_{13}=0.05 ($\sin^2 2\theta_{13}$=0.01)

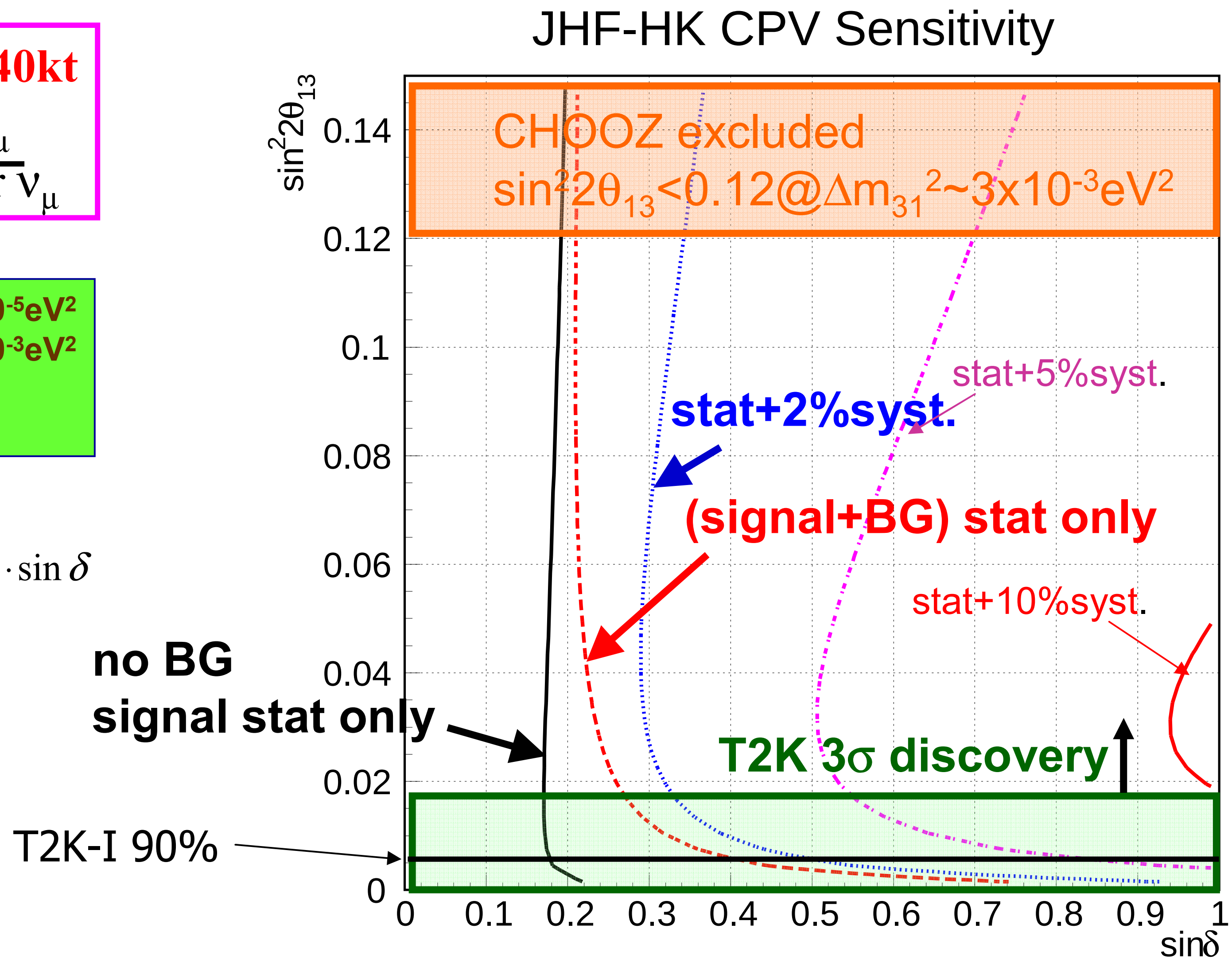
	signal		background				
	δ=0	δ=π/2	total	ν_μ	ν_μ	ν_e	ν_e
$\nu_\mu \rightarrow \nu_e$	536	229	913	370	66	450	26
$\nu_\mu \rightarrow \nu_e$	536	790	1782	399	657	297	430

Sensitivity for CPV in T2K-II

4MW, 540kt
2yr for ν_μ
6~7yr for $\bar{\nu}_\mu$

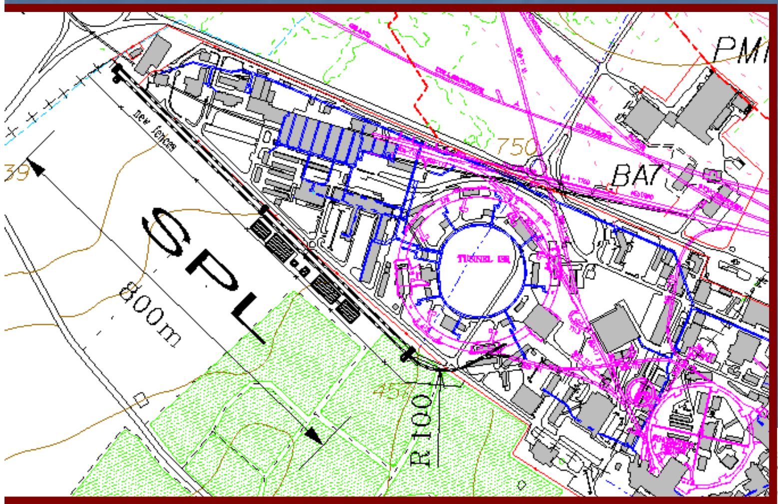
$\Delta m_{21}^2=6.9\times10^{-5}eV^2$
$\Delta m_{32}^2=2.8\times10^{-3}eV^2$
$\theta_{12}=0.594$
$\theta_{23}=\pi/4$

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

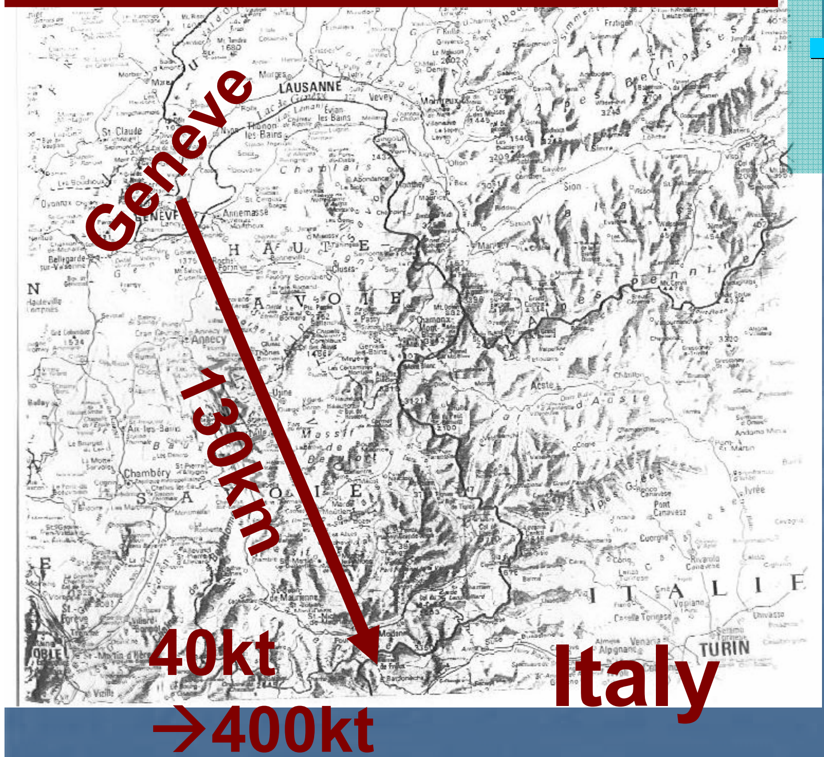


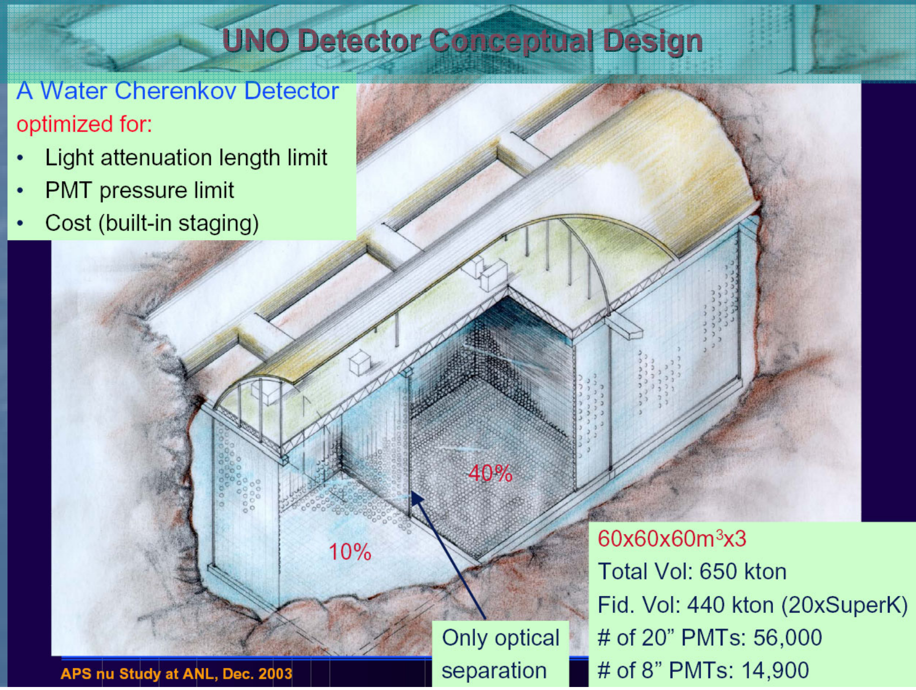
3σ CP sensitivity : |δ|>20° for $\sin^2 2\theta_{13}>0.01$ with 2% syst.

Europe: SPL→Frejus



- 4MW 2.2GeV Superconducting Proton Linac (SPL) @ CERN
- Low energy wide band ($E\nu$~0.3GeV)
- L=130km
- Water Cherenkov 40→ 400kt (UNO)
- ~18,000 $\nu\mu$ CC/year/400kt
- θ_{13}, CPV
- Small matter effect
- SPL in R&D, UNO in conceptual design

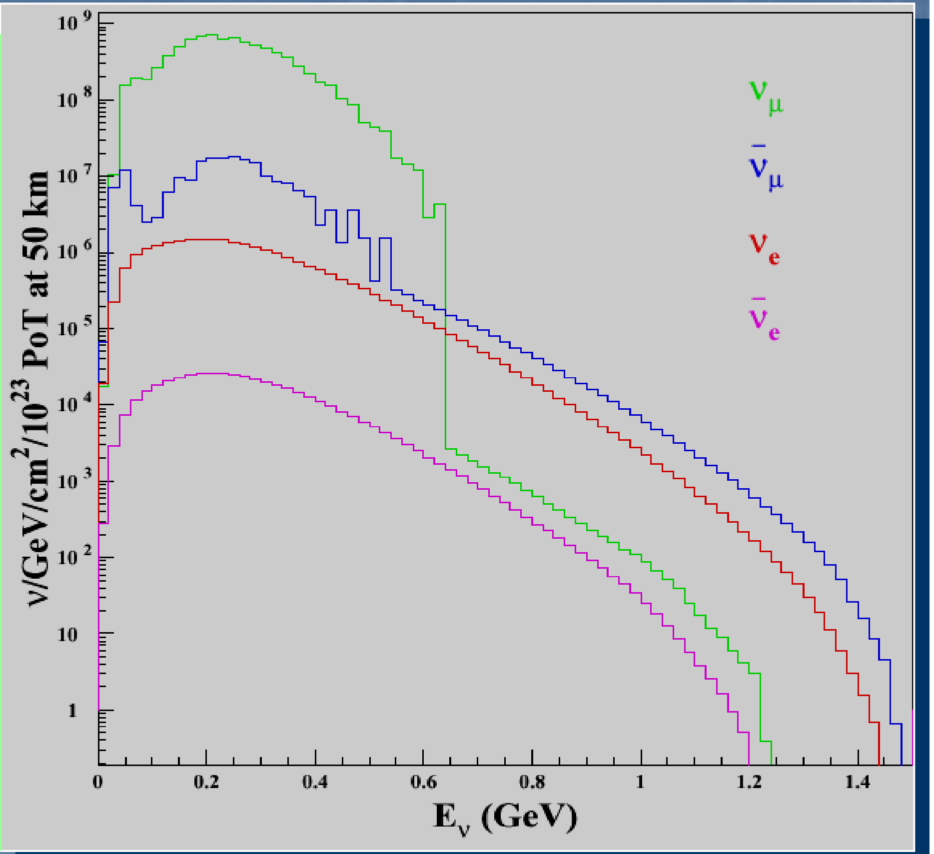




Fluxes for SPL beam

Flux intensities at 50 km from the target

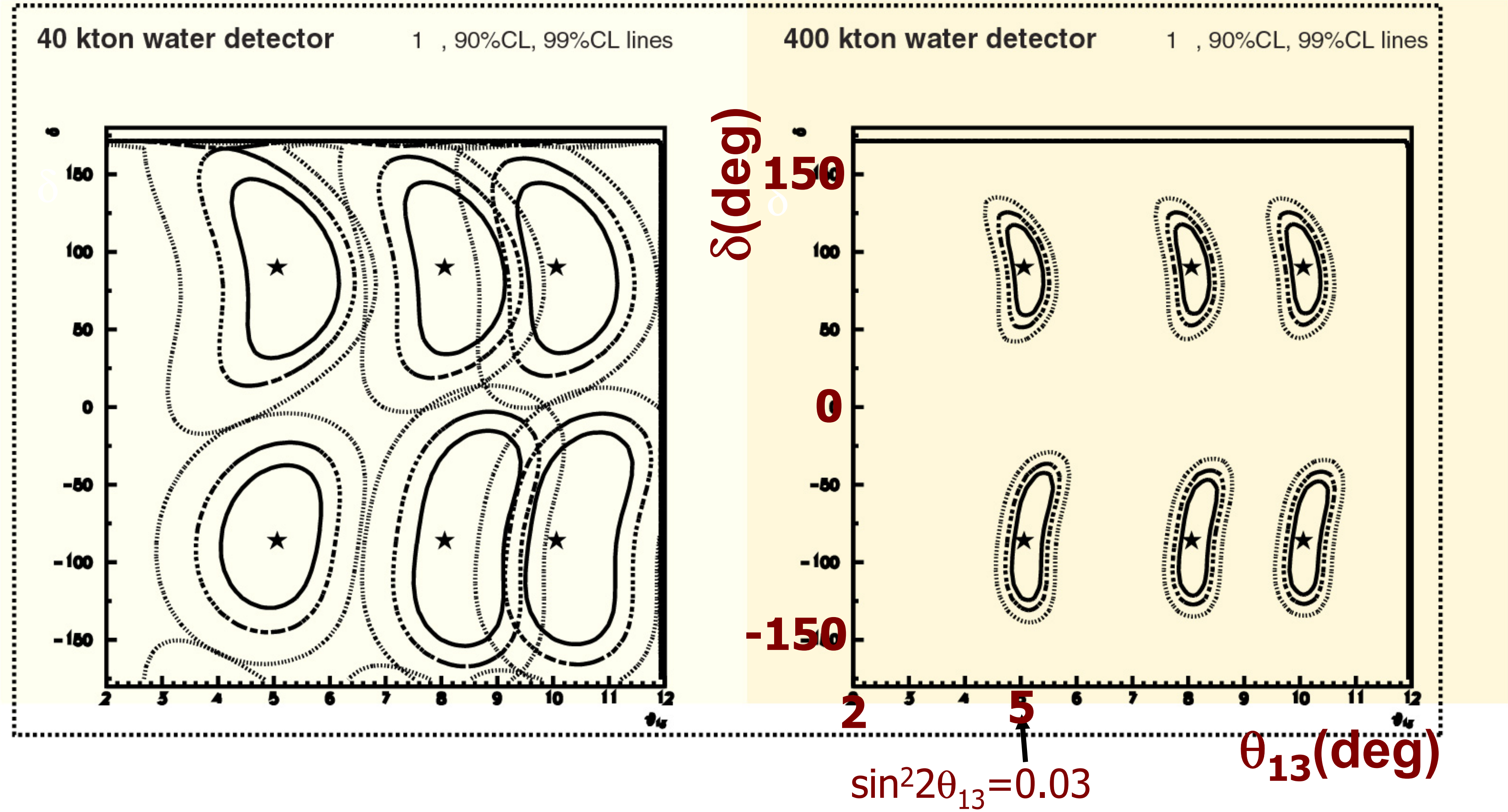
Flavour	Absolute Flux (/ 10^{23}pot / m^2)	Rel. Flux (%)	E (GeV)
μ	$3.2 \cdot 10^{12}$	100	0.27
$\bar{\mu}$	$2.2 \cdot 10^{10}$	1.6	0.28
e	$5.2 \cdot 10^{9}$	0.67	0.32
$\bar{e}$	$1.2 \cdot 10^{8}$	0.004	0.29



- Low energy wide band beam
- Less NC π^0 BG for ν_e search

Sensitivity for CPV

Preliminary CP sensitivity



M. Mezzetto, "Future Neutrino Oscillations ", Moriond, March 17, 2003. . 15

(Ref: Diwan et al., PRD68, 012002, 2003)

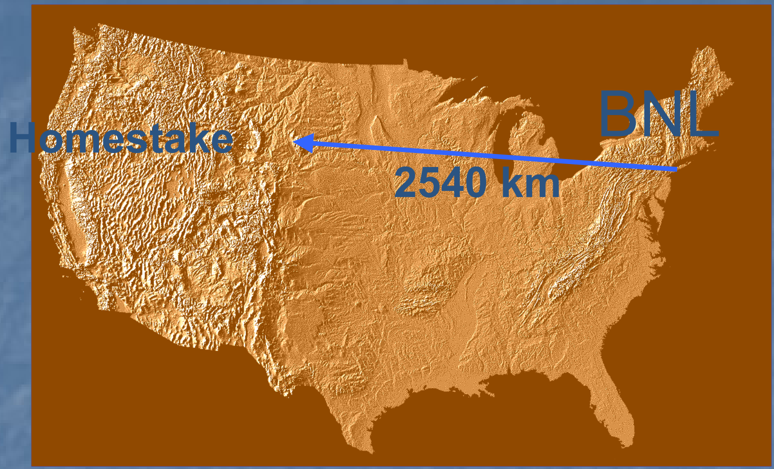
BNL-Homestake

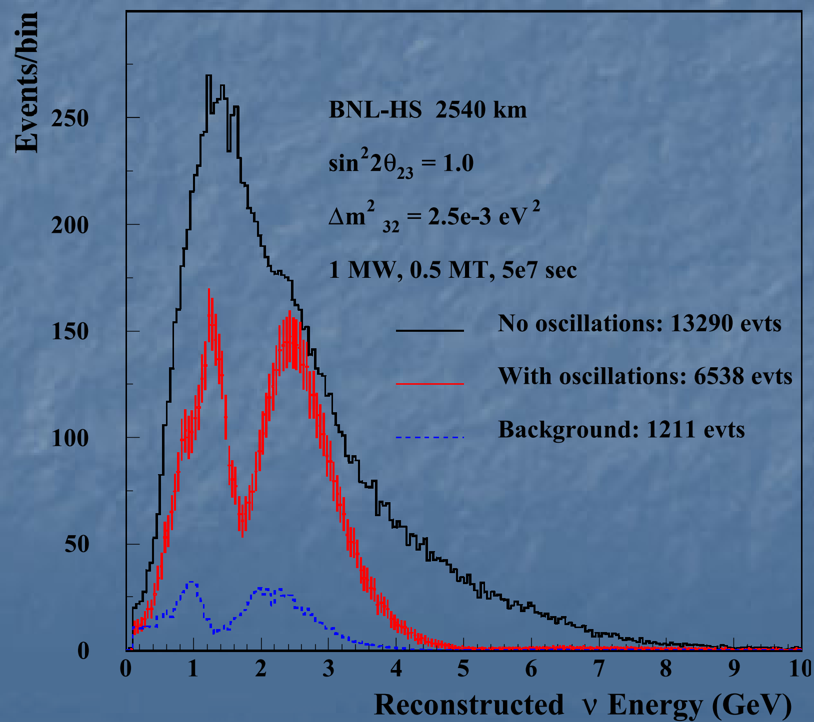
- 28GeV AGS upgrade to 1MW (2MW) cf current 0.1MW
- Wide band beam (0.5~6GeV)
- L=2,540km
- Mton UNO (alternative option: Liq. Ar.)
- ~13,000 ν_μ CC/year/500kt
- **Cover higher osc. maxima**

Goals

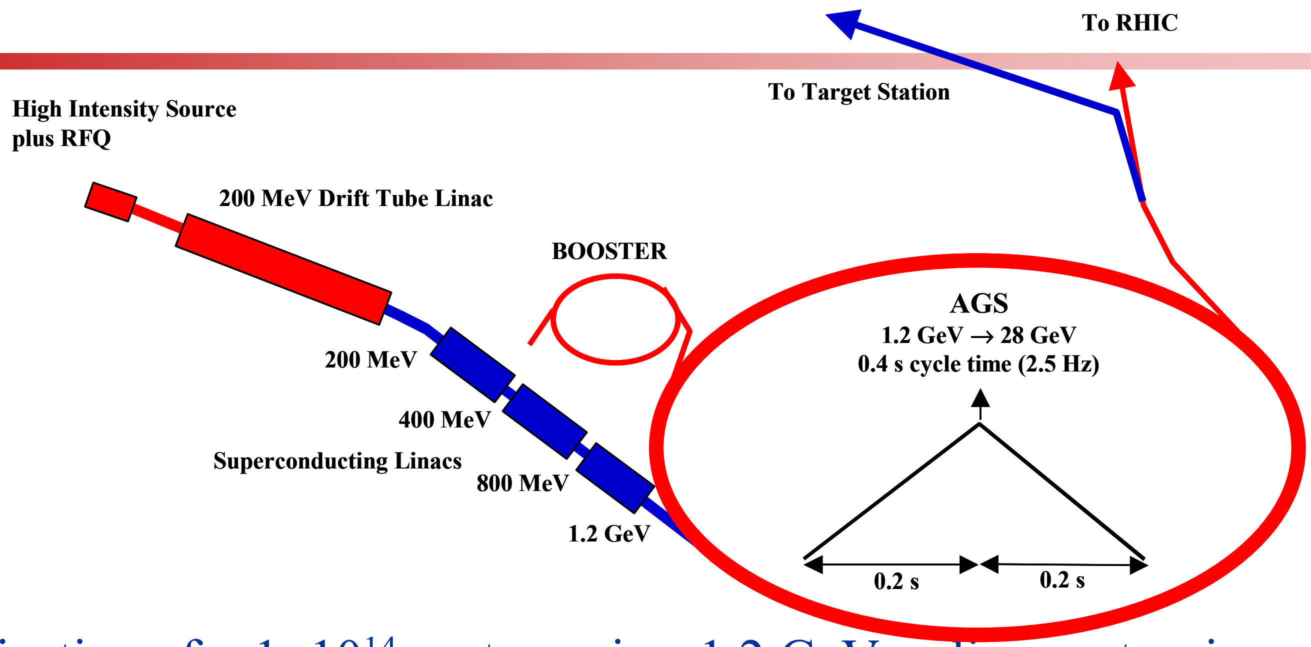
- ν_e appearance
- Sign of Δm_{23}
- CPV
- θ_{12}, Δm_{12}

Possible w/ only ν run at certain parameter region



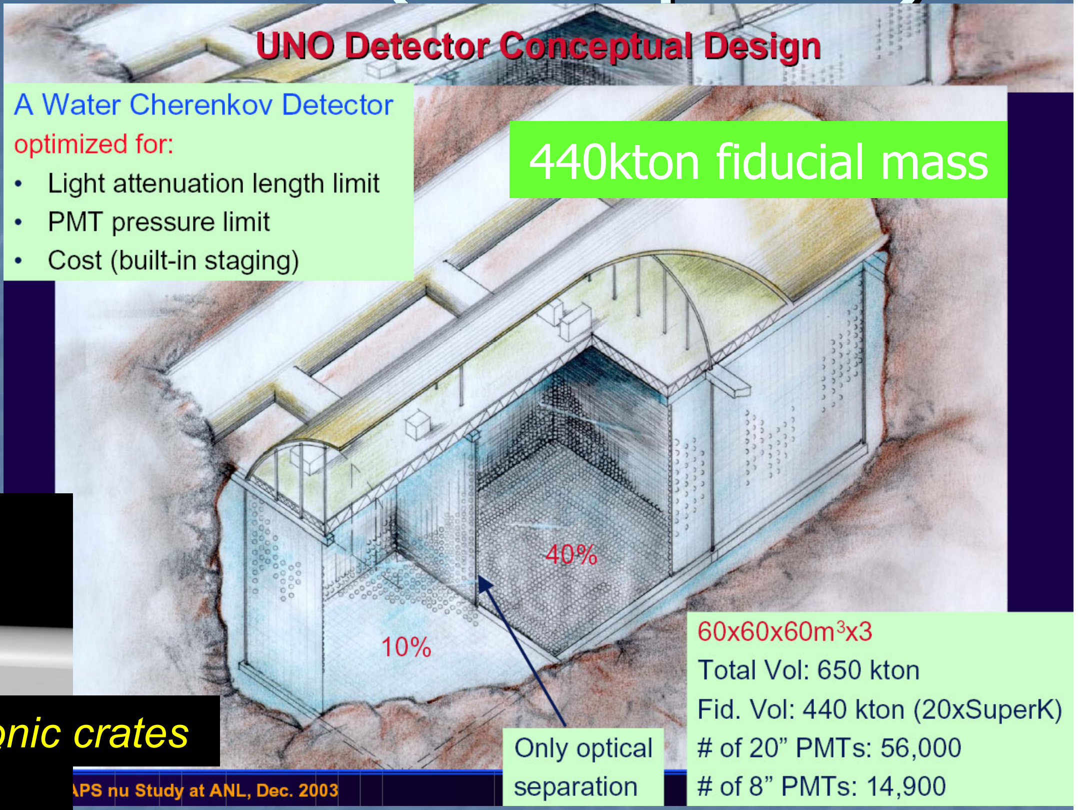


Brookhaven AGS Upgrade

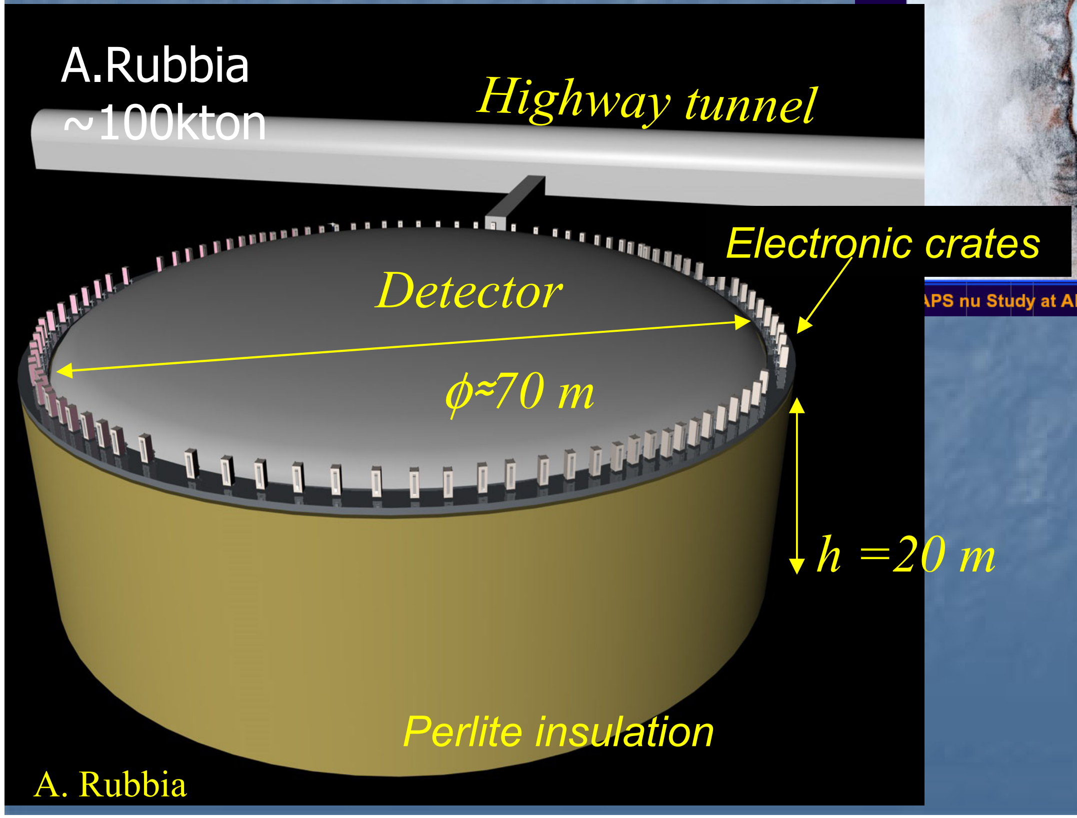


- Direct injection of ~ 1×10^{14} protons via a 1.2 GeV sc linac extension
  - low beam loss at injection; high repetition rate possible
  - further upgrade to 1.5 GeV and 2×10^{14} protons per pulse possible (x 2)
- 2.5 Hz AGS repetition rate
  - triple existing main magnet power supply and magnet current feeds
  - double rf power and accelerating gradient
  - further upgrade to 5 Hz possible (x 2)

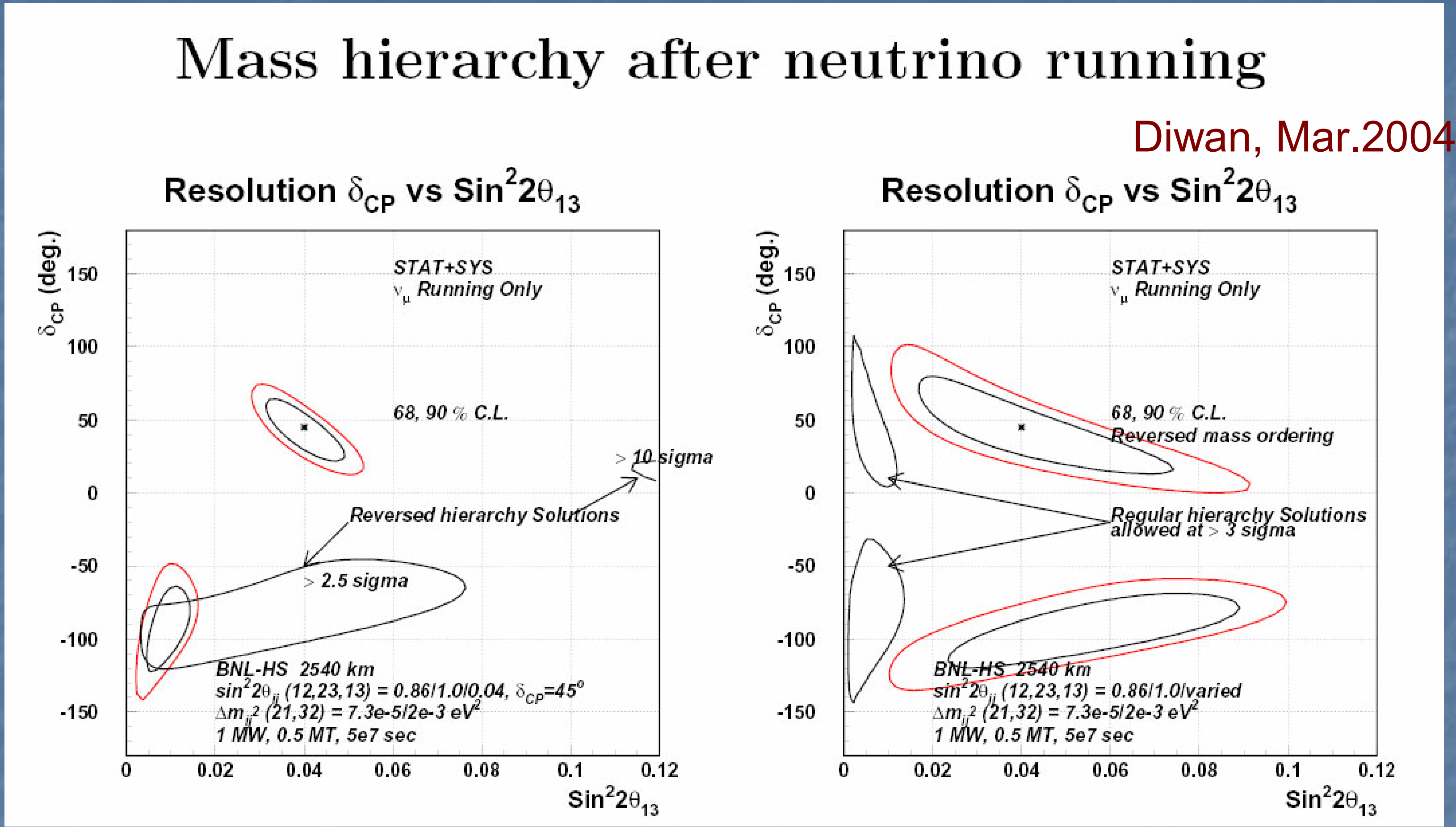
Detector options: UNO (or Liq. Ar?)



C.K.Jung



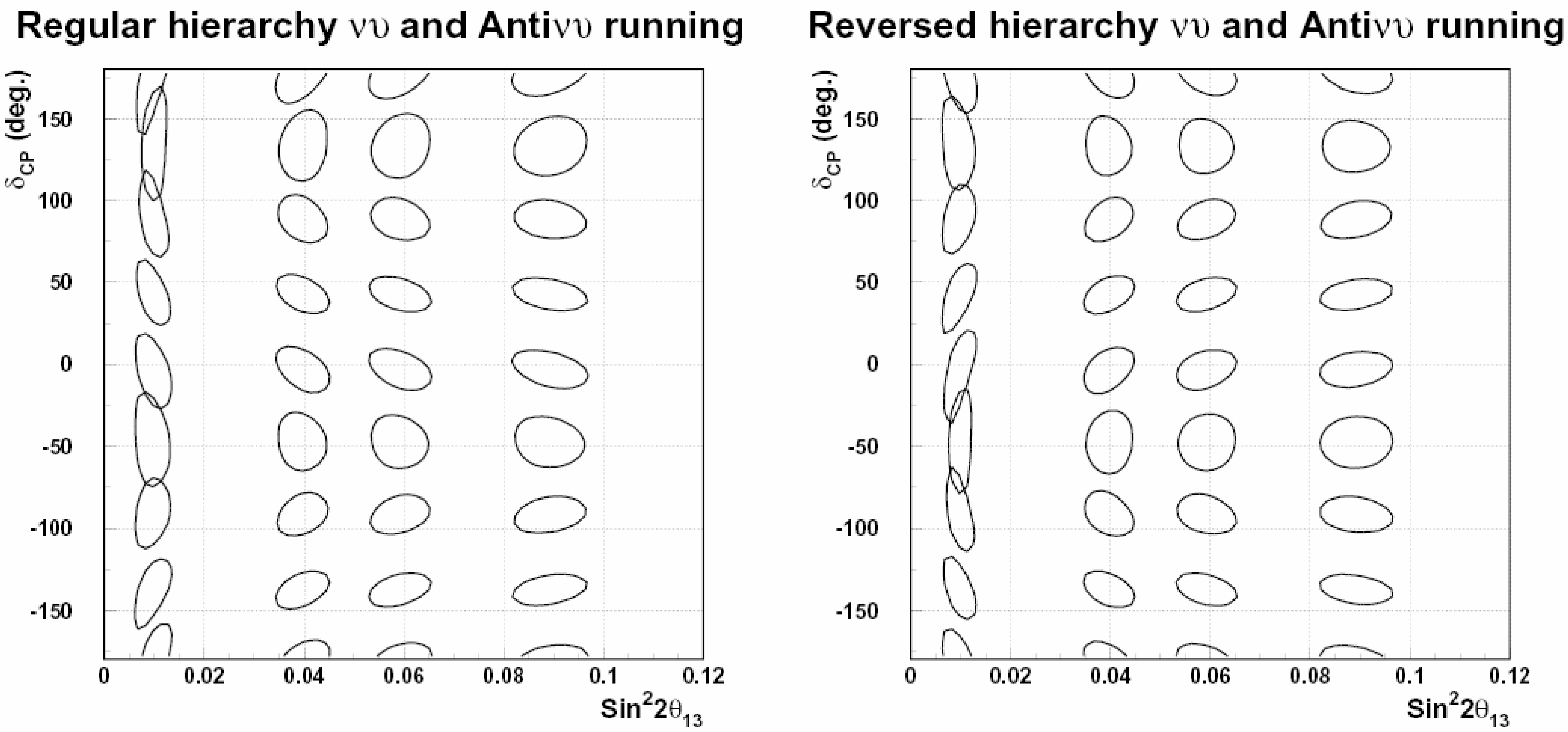
Mass Hierarchy Resolution



- w/ only ν running, reversed hierarchy rejected $>2.5\sigma$ level
- with w/ $\nu/\bar{\nu}$ running, then $>10\sigma$

Sensitivity on CPV

CP measurement after nu and anti-nu



Diwan, Mar.2004

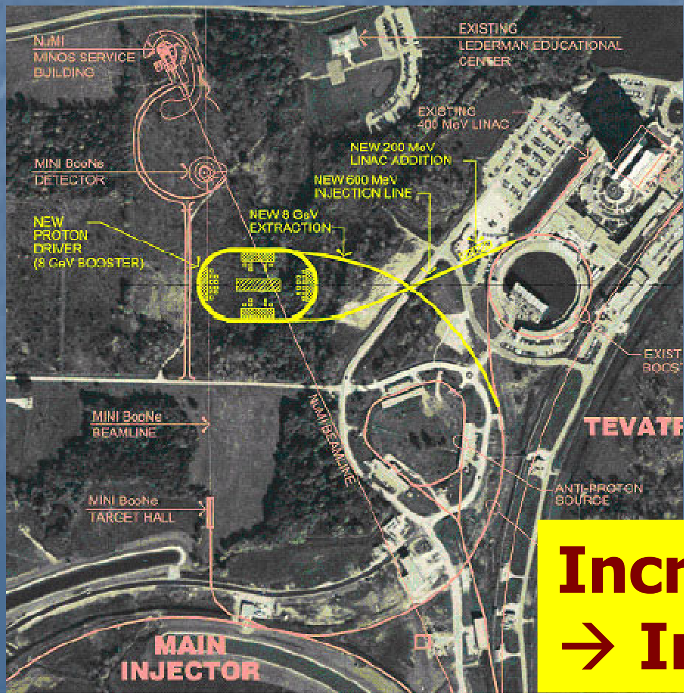
Fermilab Proton Driver (PD)

Replace injector for Main Injector

8 GeV synchrotron option

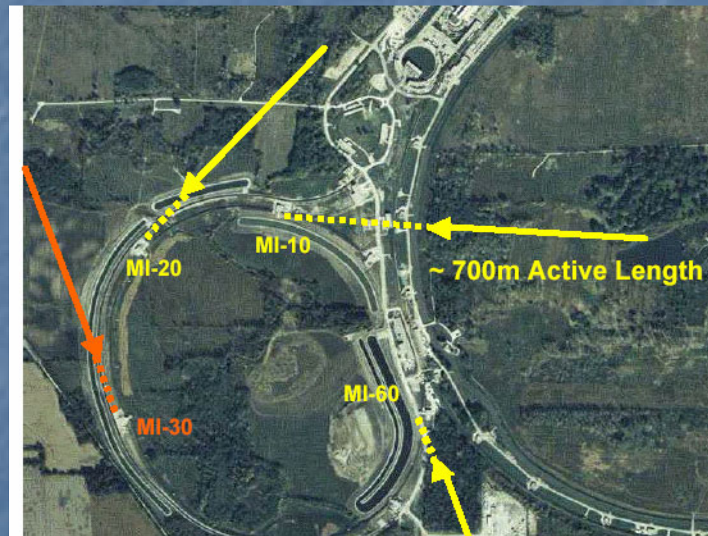
- Original concept (May 2002, Fermilab-TM-2169)
- Large aparture (100x150mm) magnets
- LINAC 400MeV → 600MeV
- MI cycle time 1.87s → 1.53s

→ Net results : MI power of 1.9MW



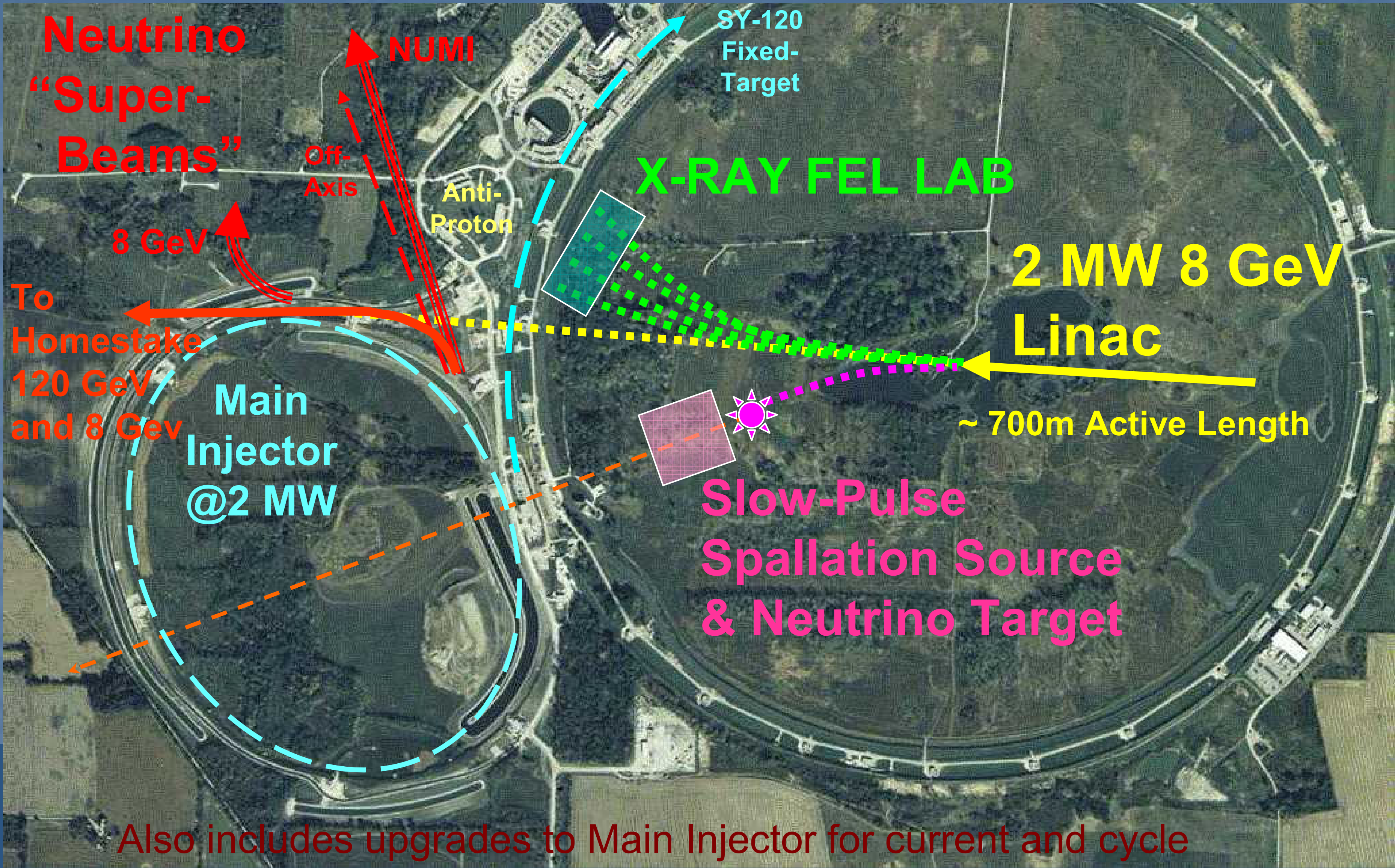
8 GeV superconducting linac

- Recent study
- Direct injection
- 2MW @ 8GeV & 40~120GeV(MI)
- Future flexibility
- Issue: Cost?

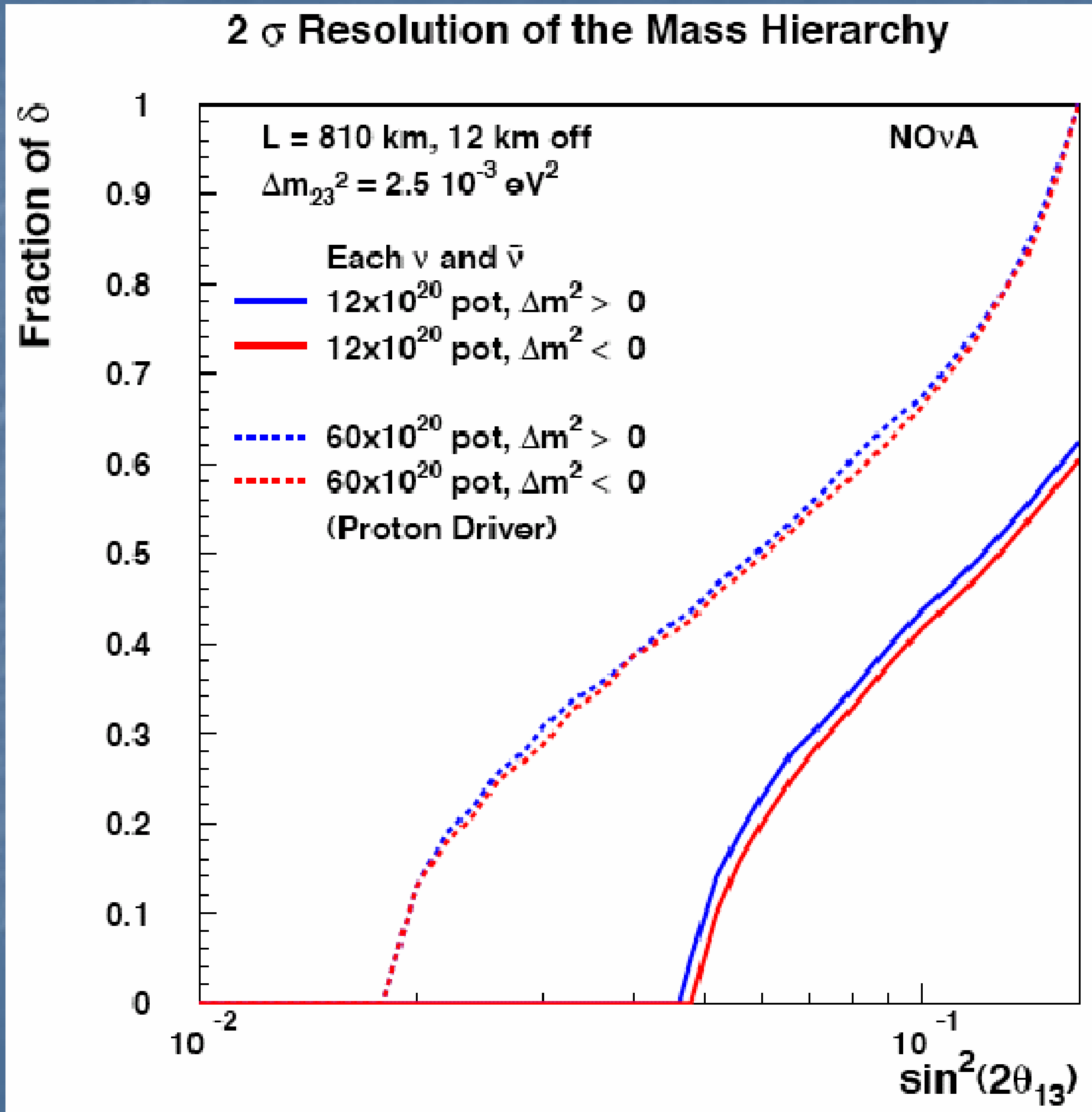


Increase MI power by x5~6 (2MW)
→ Improve MINOS & NOνA sensitivities

Potential Flexibility of LINAC

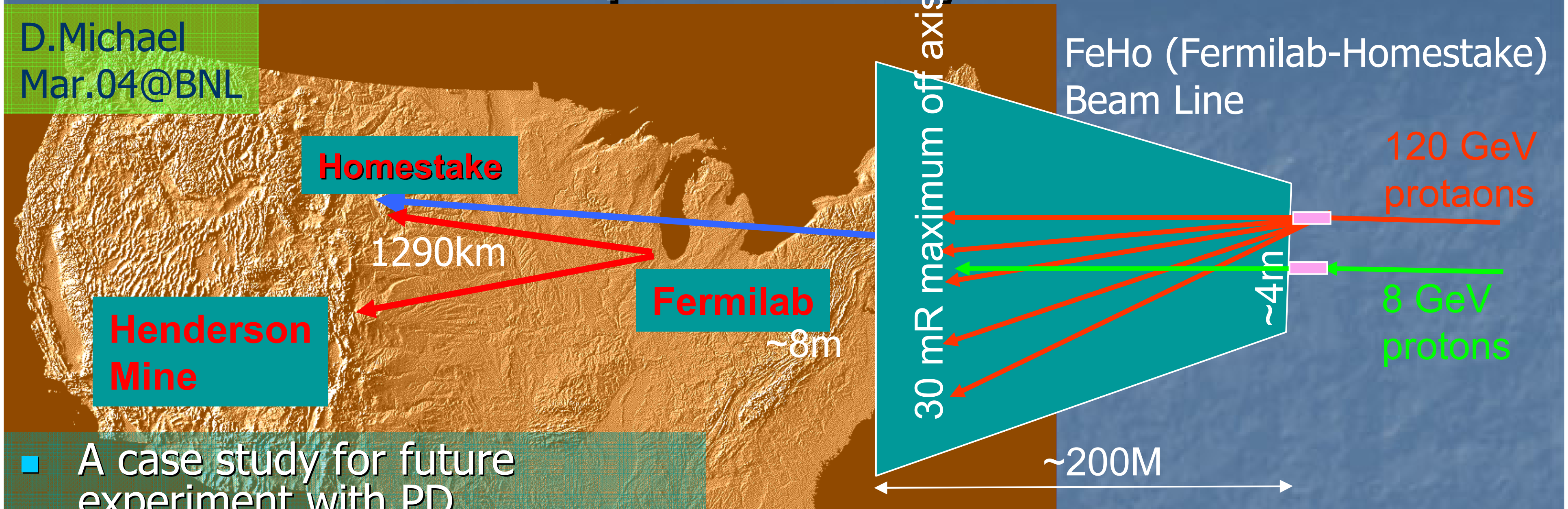


NOνA + PD : Mass hierarchy

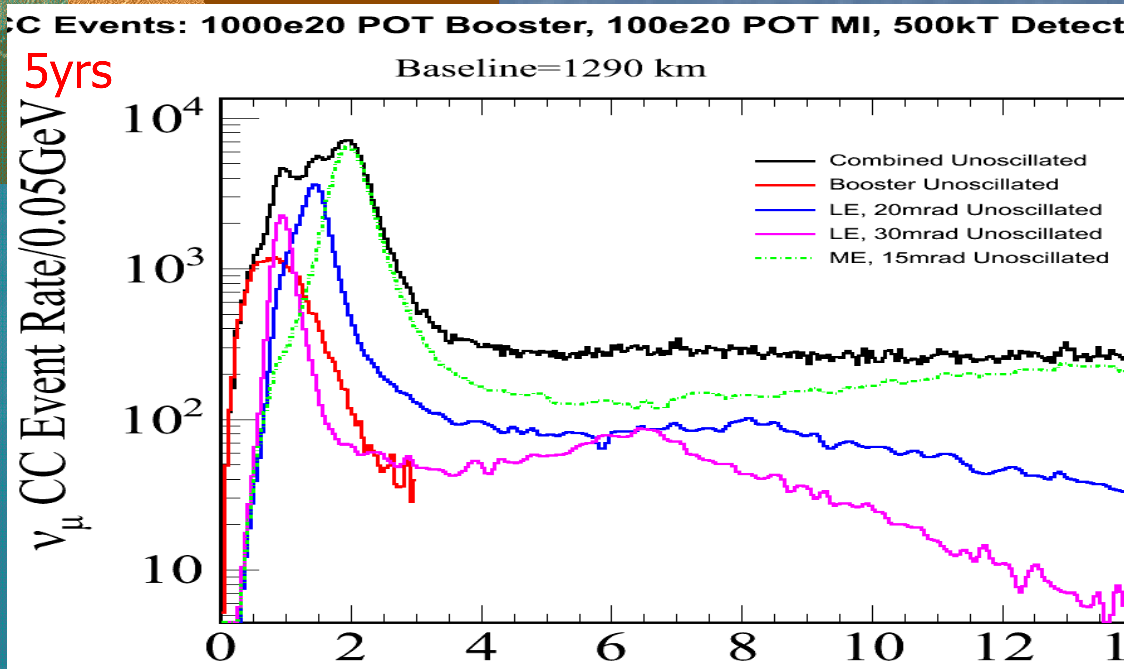


G.Feldman
Jun.04

Another possibility with PD



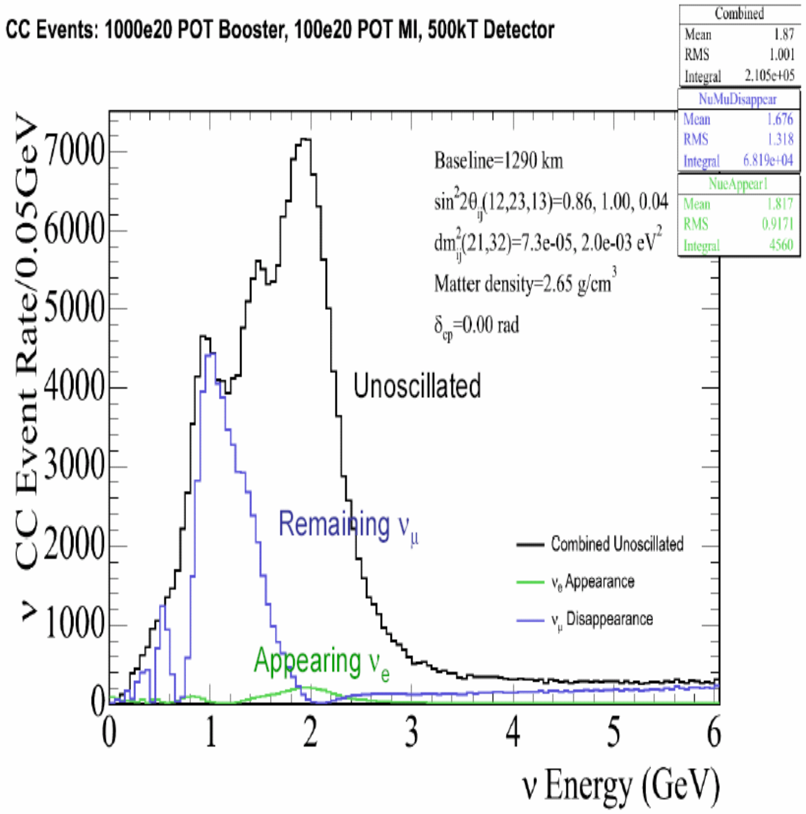
- A case study for future experiment with PD
- 2MW 8/120GeV PD→ "4MW"
- WB/OA to Homestake @1290km (or Henderson)
- Eν=0.5~3GeV
- Cover higher osc max
- 500kt WC or 100kt Liq.Ar
- ~50k νμ CC/year/500kt
- Studies of physics potential started

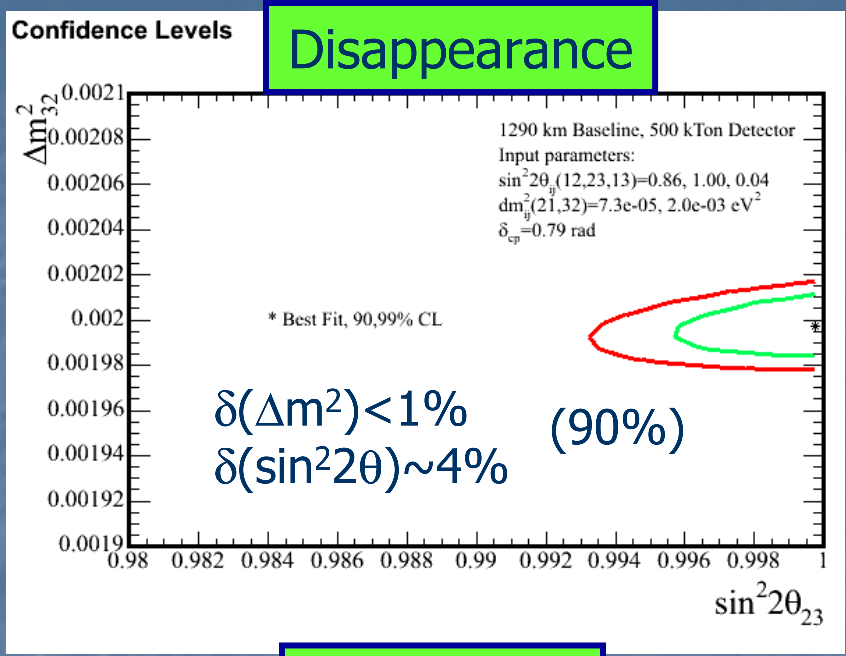


Sensitivities with 500kt Water C

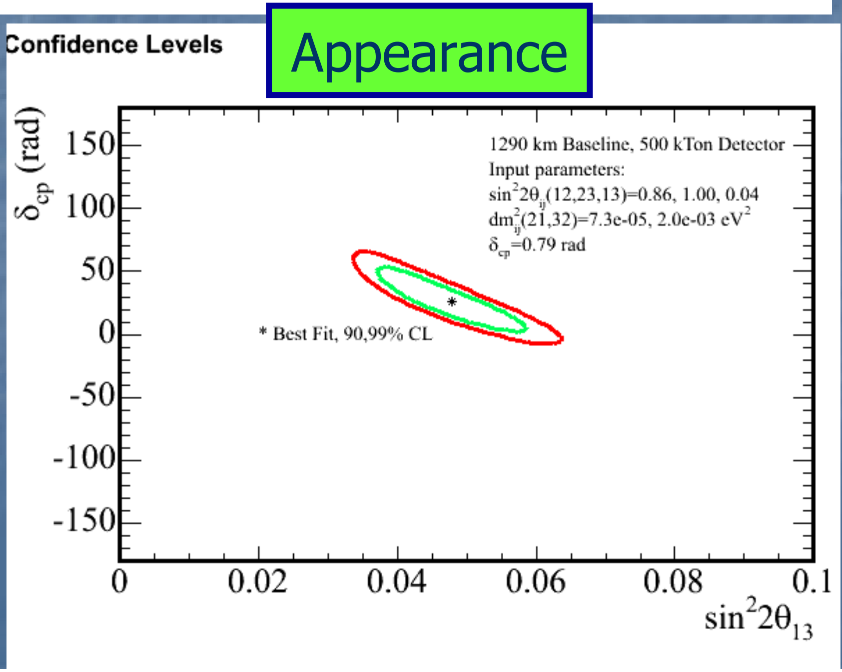
D.Michael
May 04, FNAL

5yrs running





$\delta(\Delta m^2)<1\%$
$\delta(\sin^2 2\theta)\sim 4\%$ (90%)



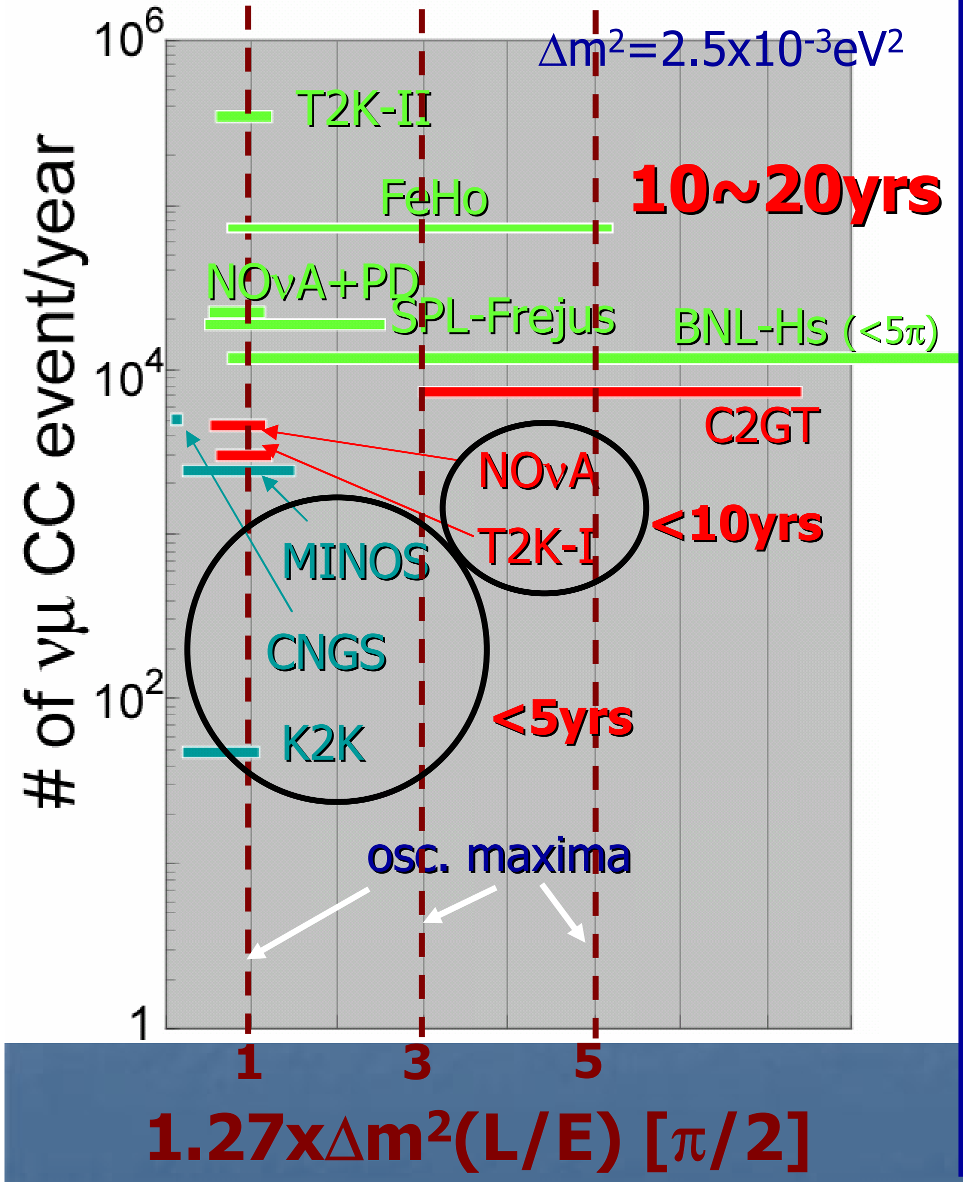
100kt Liq Ar could be better thanks to det. resolution
Studies in progress.

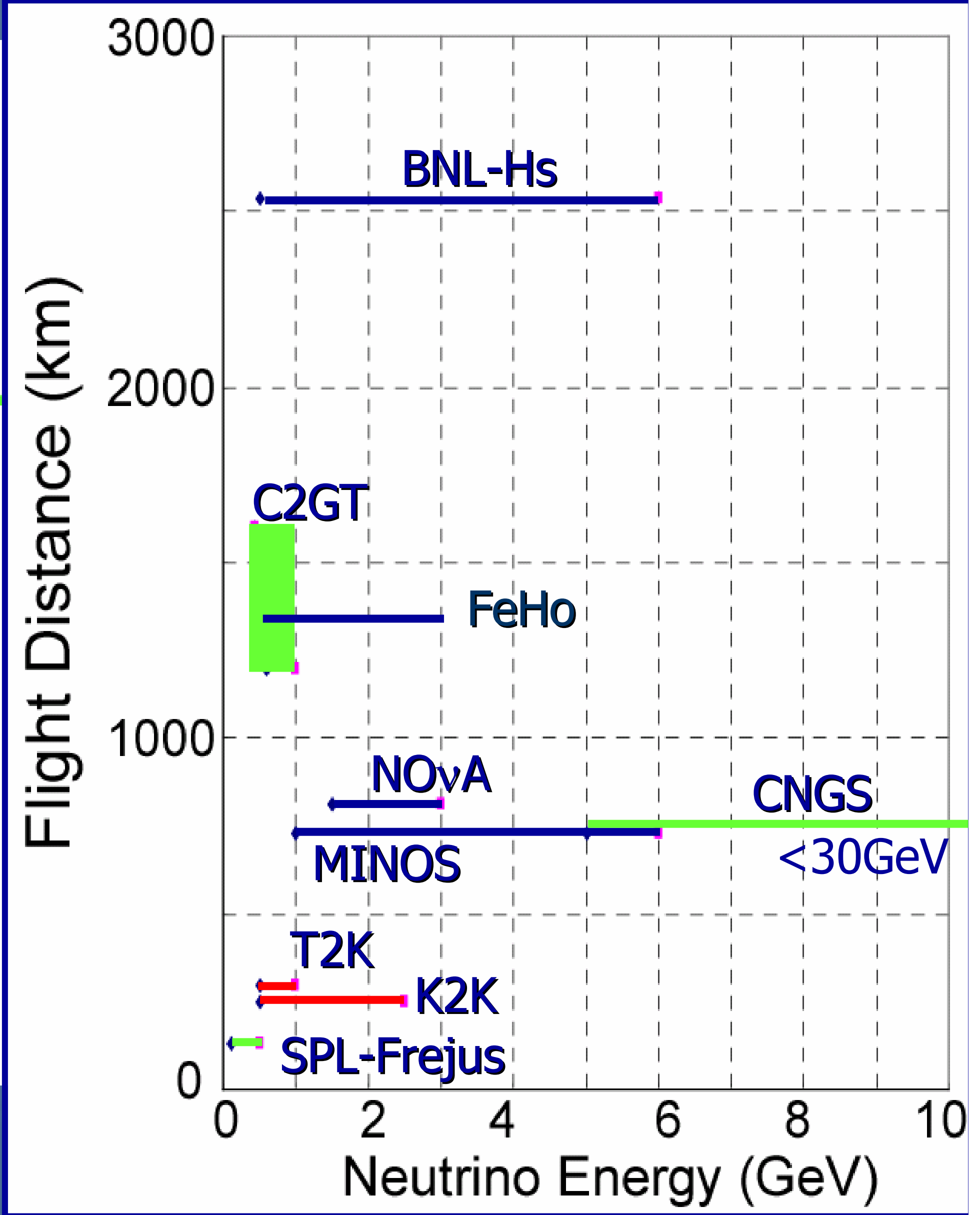
Summary of ("super-beam") LBL experiments

	E_p (GeV)	Power (MW)	Beam	$\langle E_\nu \rangle$ (GeV)	L (km)	M_{det} (kt)	ν_μCC (/yr)	ν_e @peak	
K2K	12	0.005	WB	1.3	250	22.5	~50	~1%	
MINOS(LE)	120	0.4	WB	3.5	730	5.4	~2,500	1.2%	I
CNGS	400	0.3	WB	18	732	~2	~5,000	0.8%	
T2K-I	50	0.75	OA	0.7	295	22.5	~3,000	0.2%	
NOνA	120	0.4	OA	~2	810?	50	~4,600	0.3%	II
C2GT	400	0.3	OA	0.8	~1200	1,000?	~5,000	0.2%	
T2K-II	50	4	OA	0.7	295	~500	~360,000	0.2%	
NOνA+PD	120	2	OA	~2	810?	50?	~23,000	0.3%	
BNL-Hs	28	1	WB/OA	~1	2540	~500	~13,000		III
SPL-Frejus	2.2	4	WB	0.32	130	~500	~18,000	0.4%	
FeHo	8/120	"4"	WB/OA	1~3	1290	~500	~50,000		

(grey box) Running, constructing or approved experiments

"Graphical" Summary of experiments





Summary

- Next generation "Super Beam" experiments will provide chances to clarify whole view of ν mixing
  - θ_{13}
  - CPV, sign of Δm^2, ..
  - High precision measurements of parameters
- Several experiments are under consideration
  - (Multi-)MW beam + Mton detector (or Liq.Ar)
  - Japan: 4MW 50GeV @ J-PARC → Mt Hyper-Kamiokande
  - Europe: 4MW 2.2GeV SPL → Mt UNO
  - US-BNL: 1(2)MW AGS → UNO(Liq.Ar)@~2500km
  - US-FNAL: 2MW PD/MI → NOνA/ UNO(liq.Ar)@~1300km
- Future direction much depend on results from "2nd phase" experiments
  - T2K-I(2009~) and NOνA(if approved)
- Let's do experiments to know θ_{13} (2nd phase) ASAP!!,
  - While keeping R&D efforts for future projects
  - (while reducing too many meeting!)