ν '04
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Paris

Super Beams

Takashi Kobayashi
IPNS, KEK

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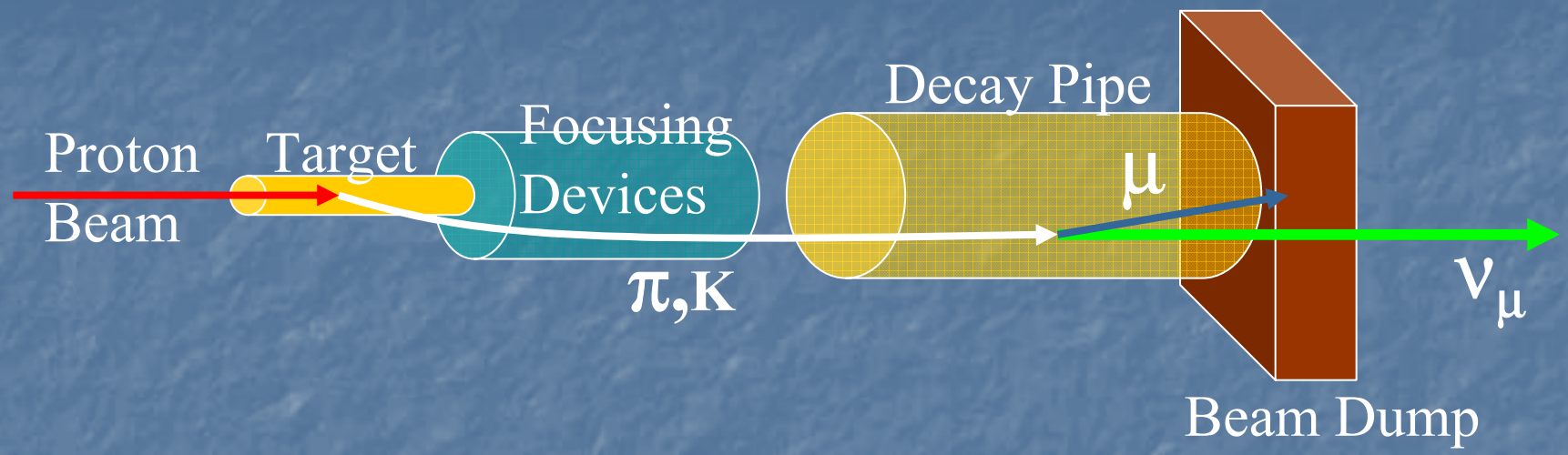
What is (Original) Super Beam?



Conventional neutrino beam with (Multi-)MW proton beam

- Pure ν_μ beam ($\gtrsim$99%)
- ν_e ($\lesssim$1%) from $\pi \rightarrow \mu \rightarrow e$ 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
  - Confirmation of atm. ν results
    - K2K(1999~)/MINOS(2005~)/ICARUS/OPERA(2006~)
  - Experiments "realized"
- 2nd phase experiments
  - **Discovery of ν_e appearance**
  - Designed & Optimized aft. SK atm ν
  - ~MW beam w/ ~50kton detector
    - T2K-I (approved. 2009~)/NOνA (2009?~) / (C2GT)
- 3rd phase experiments
  - **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

My "Super Beam" Experiments

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

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

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

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

Matter eff.:

$$a = 7.56\times10^{-5}[\mathrm{eV}^2]\cdot\left(\frac{\rho}{[\mathrm{g/cm}^3]}\right)\cdot\left(\frac{E}{[\mathrm{GeV}]}\right)$$

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

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

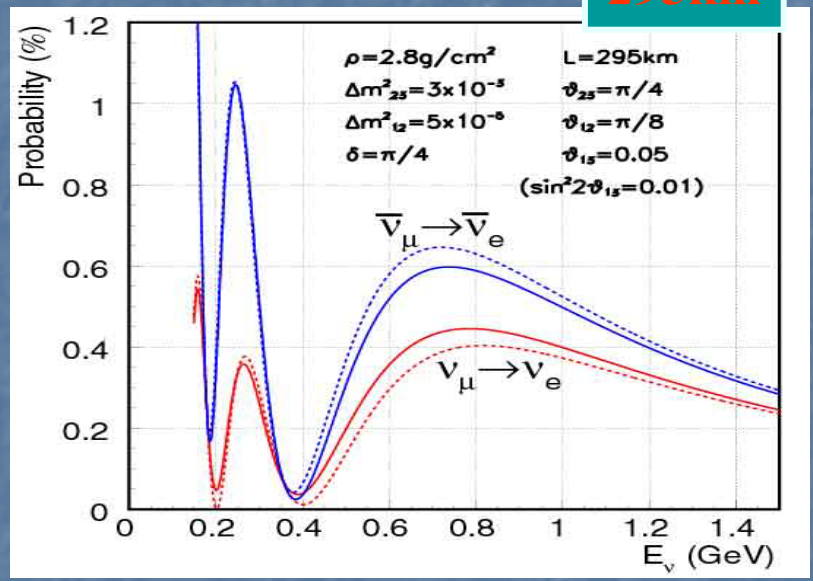
Sensitivity indep. from θ_{13} (if no BG & no syst. err)

CPV vs matter effect

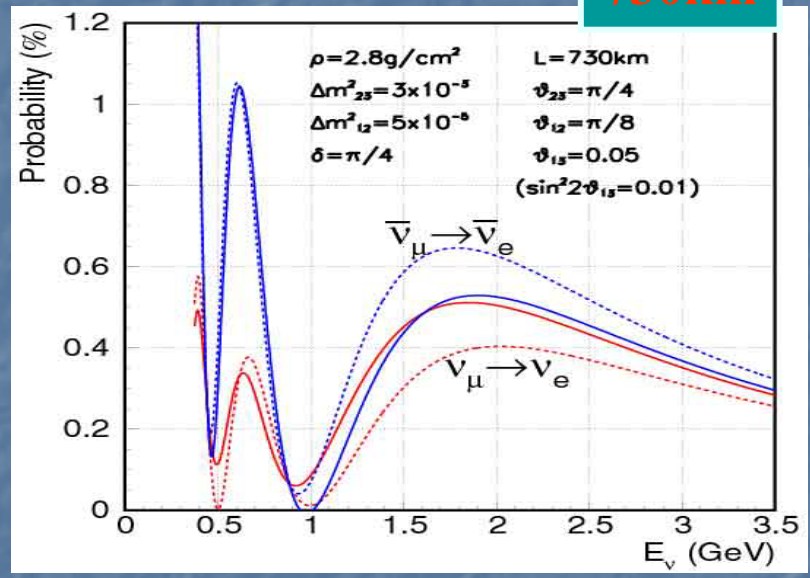
$\nu_\mu \rightarrow \nu_e$ osc. probability w/ CPV/matter

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

295km



730km

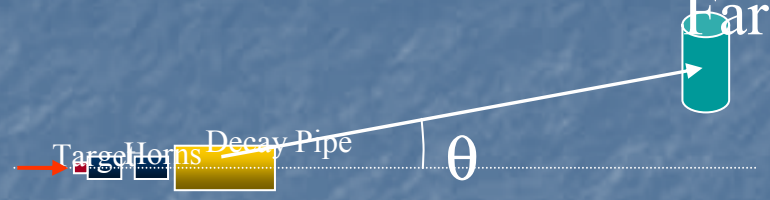


@$\sin^2 2\theta_{13}$=0.01

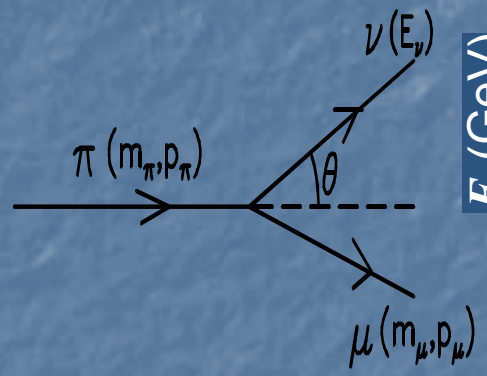
Smaller distance/lower energy → small matter effect
Pure CPV & Less sensitivity on sign of Δm^2
Combination of diff. E&L help to solve.

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

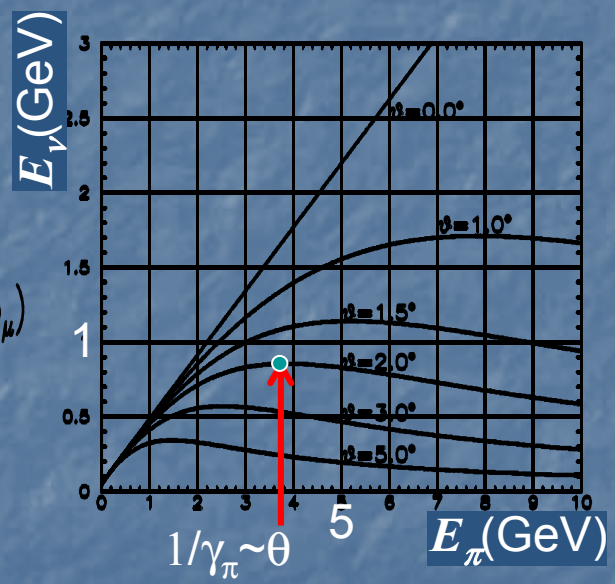
(ref.: BNL-E889 Proposal)



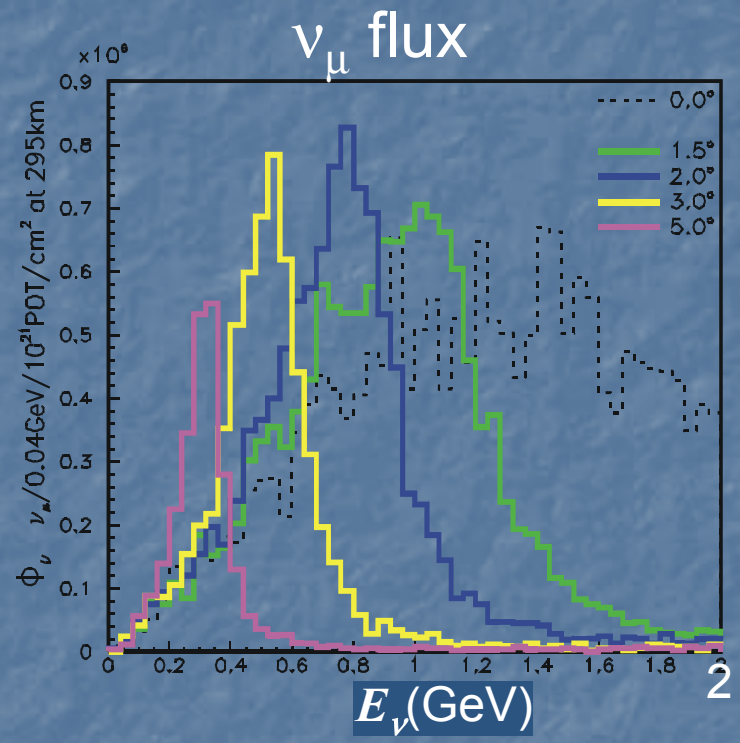
Decay Kinematics



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



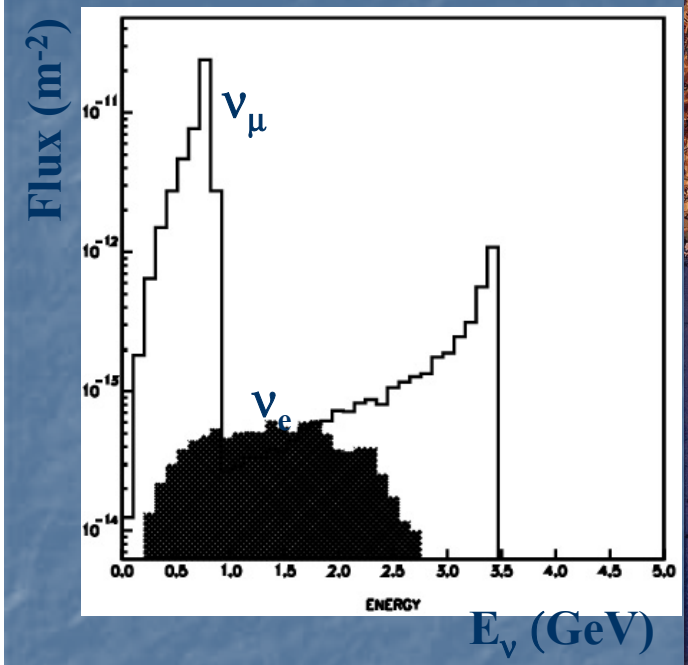
$$E_\nu^{\max}[\mathrm{GeV}] \approx \frac{30}{\theta[\mathrm{mrad}]}$$

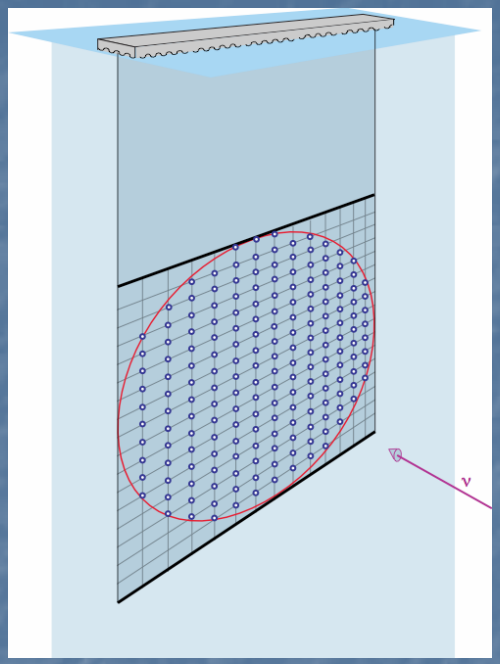


- Increase statistics @ osc. max.
- Decrease background from HE tail

Idea of C2GT (CNGS to Gulf of Taranto)

F.Dydak et.al.

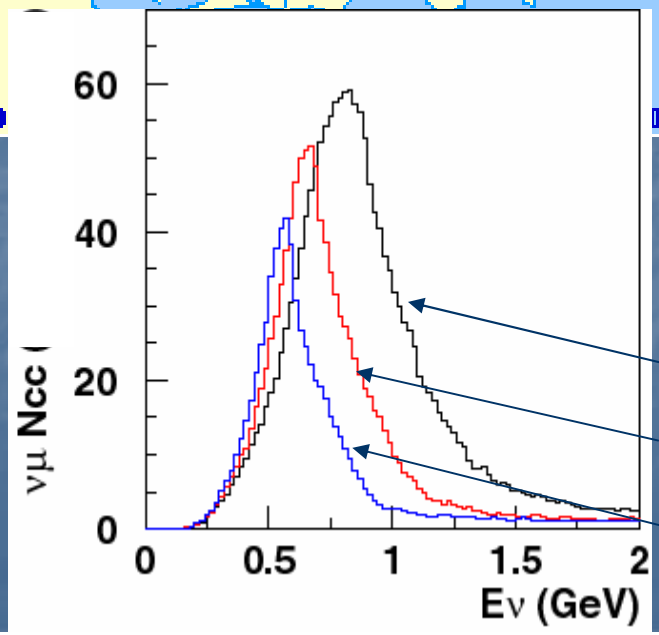




- OA-CNGS
- Movable underwater Cherenkov det. (r=150m), 2Mt fid vol, L=1,200~1,600km
- ~5,000 $\nu\mu$ CC/year
- Disappearance & Appearance
- $\sin^2 2\theta_{13}$~0.008 @90%
- Technology to be established (underwater, light collection, LE PID,…)

T2K-II

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

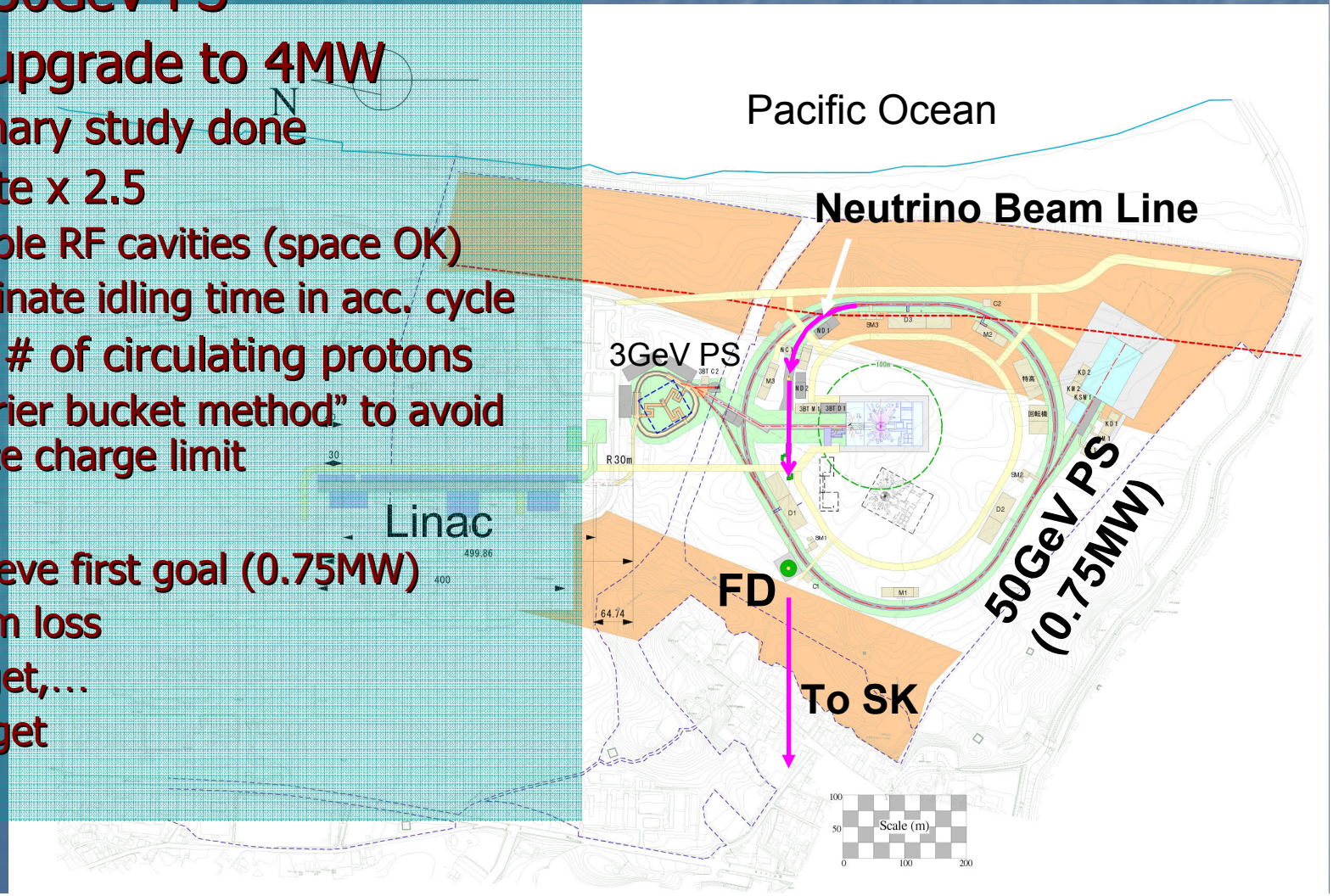


OAB2.0deg
OAB2.5deg
OAB3.0deg

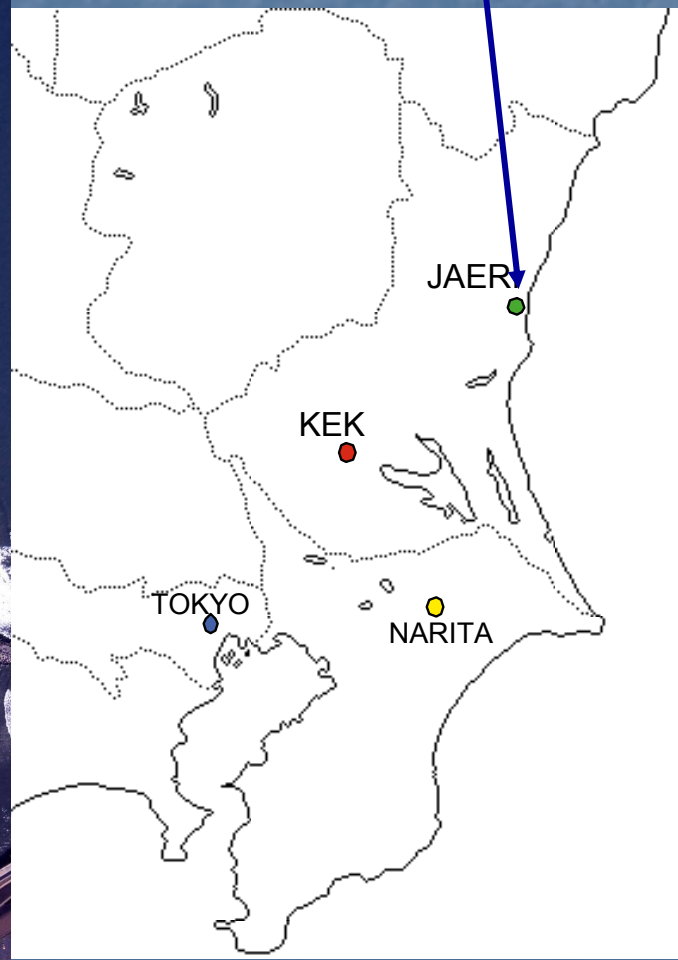
J-PARC
(Japan Proton Accelerator Research Complex)

(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,…
    - Budget



J-PARC



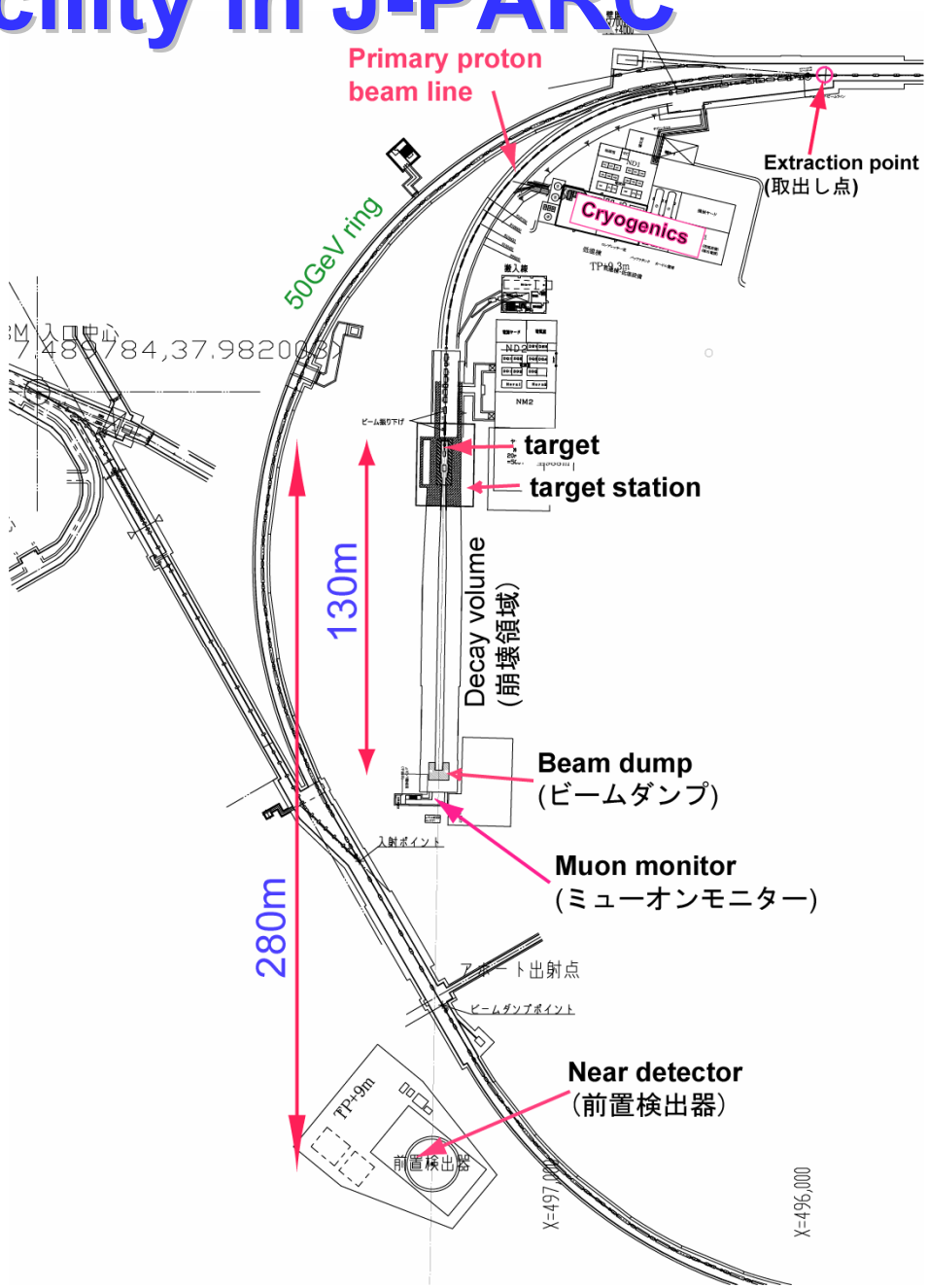
Neutrino facility in J-PARC

Special Features

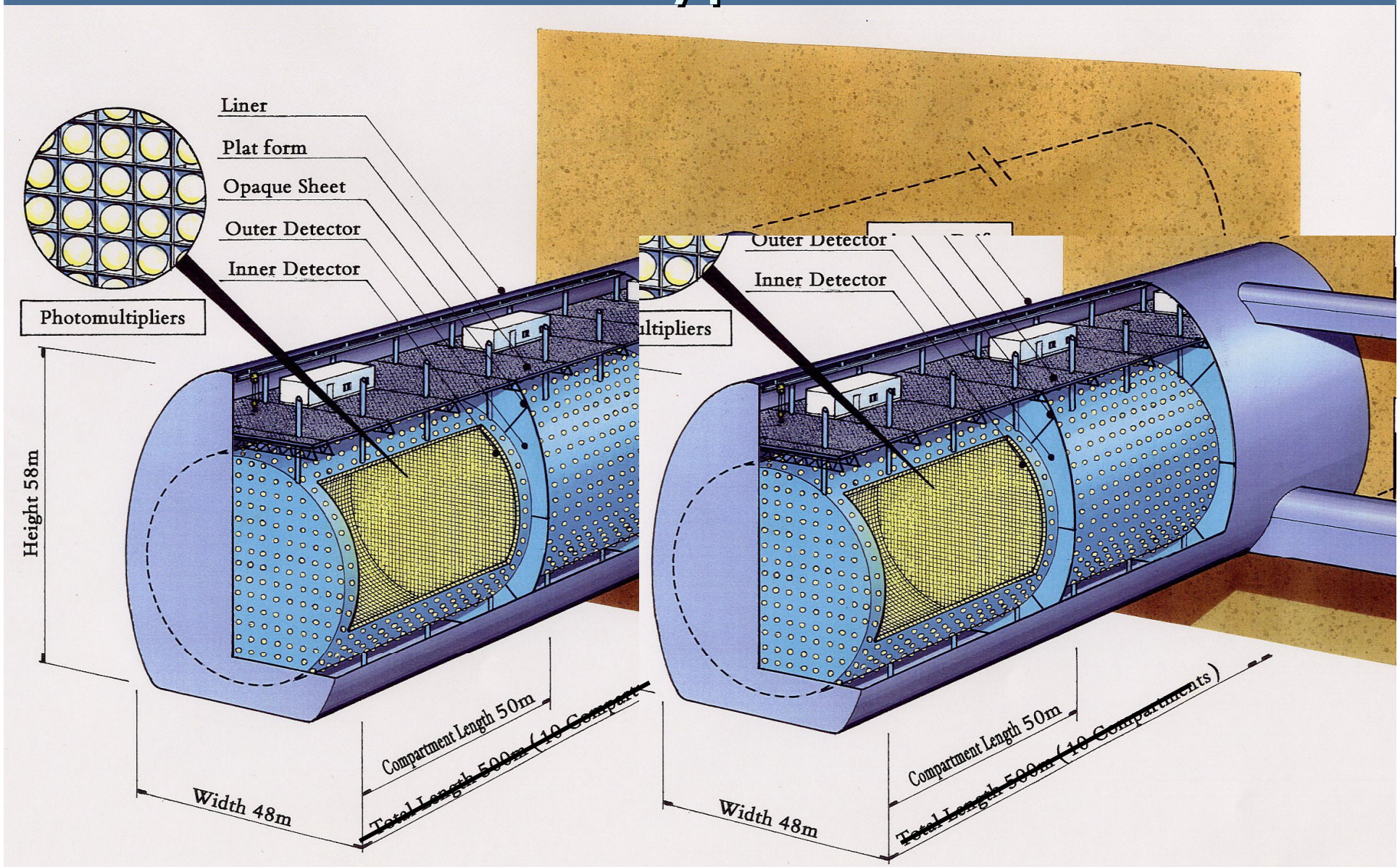
- Superconducting combined function magnets
- Off-axis beam
  - 2~3 deg adjustable

Approved in Dec.2003

- 5 year construction Apr.2004~Mar.2009
- 16.0B yen (~160M$)

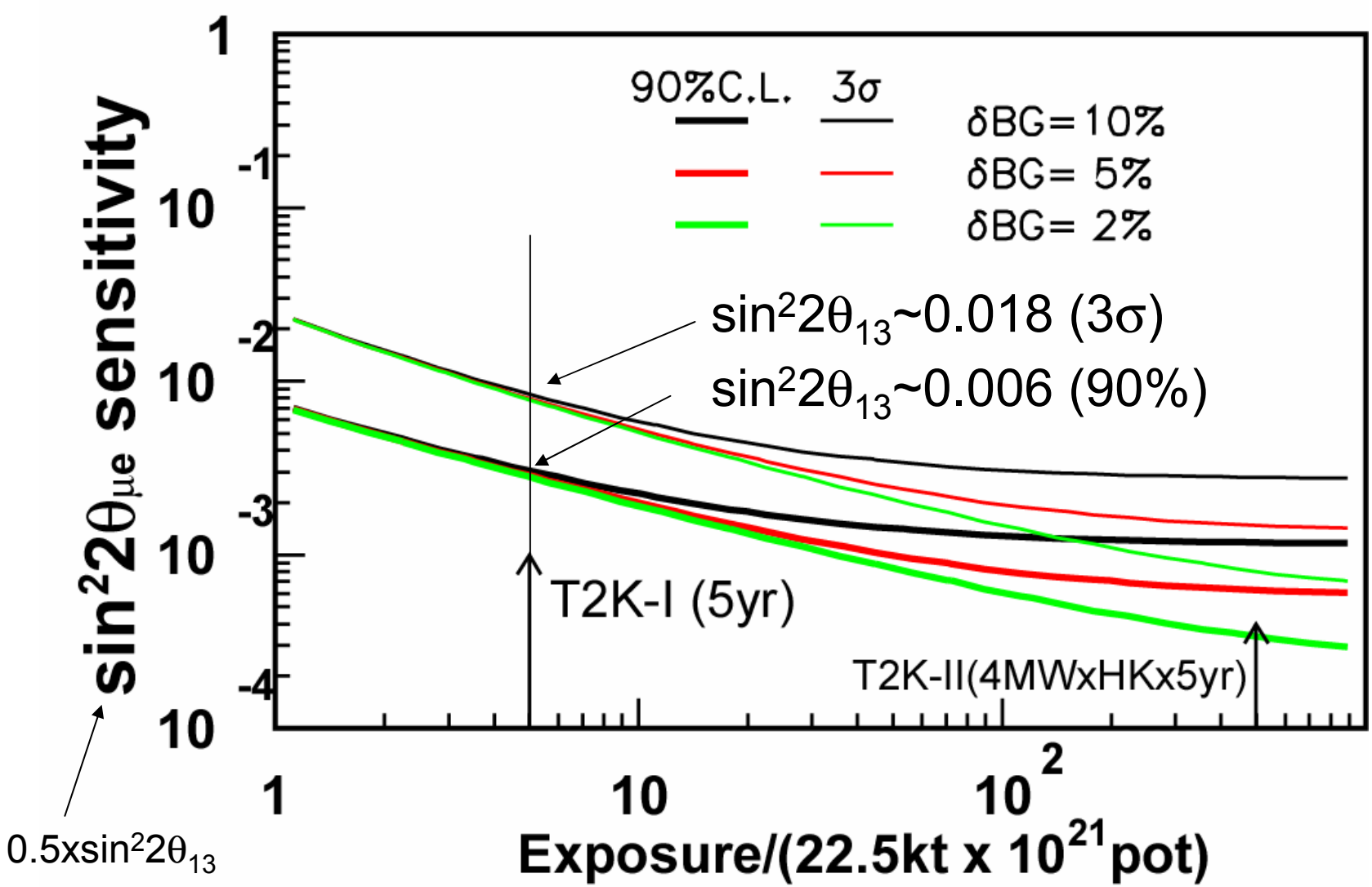


Far Detector: Hyper-Kamiokande



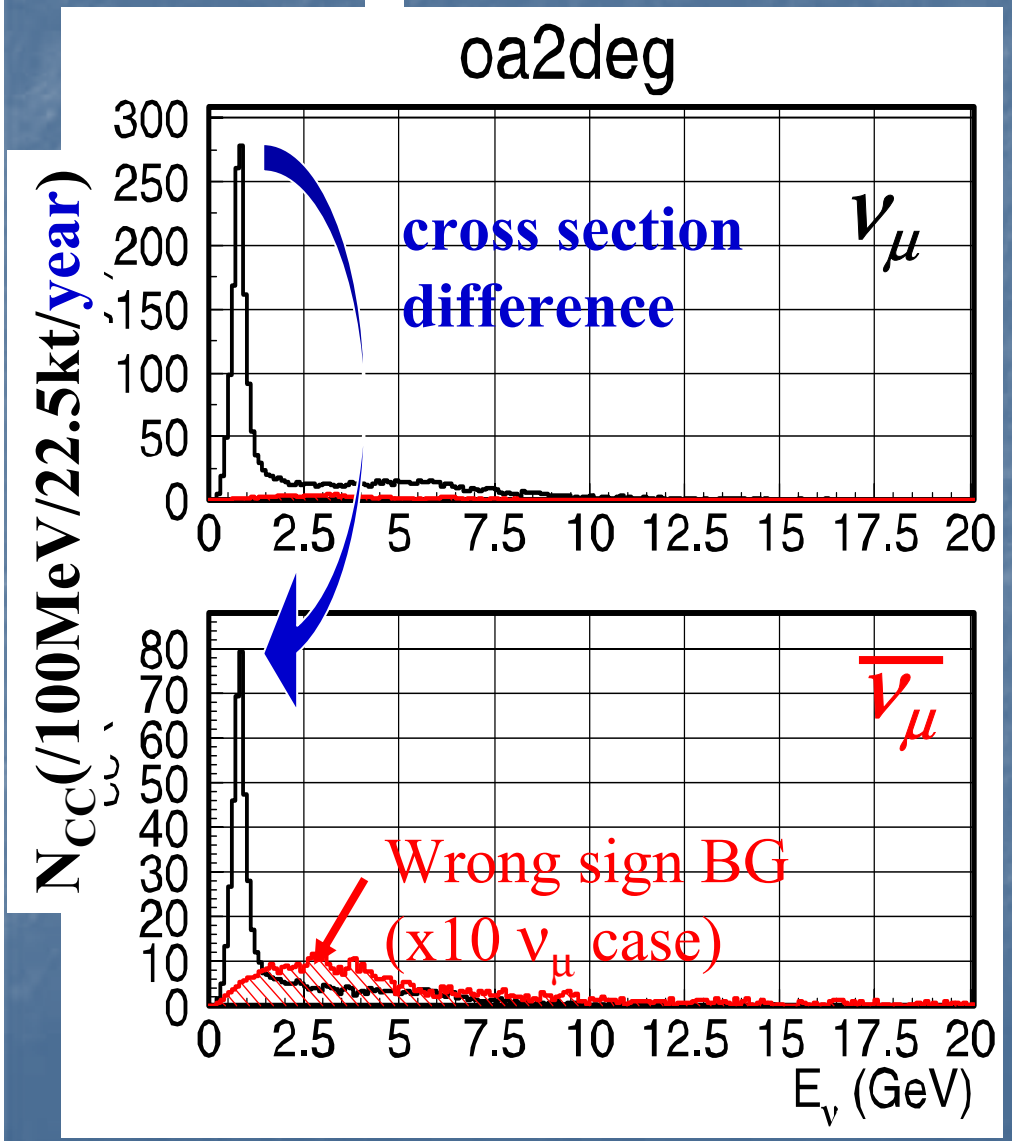
2 detectors × 48m × 50m × 250m, Total mass = 1 Mton

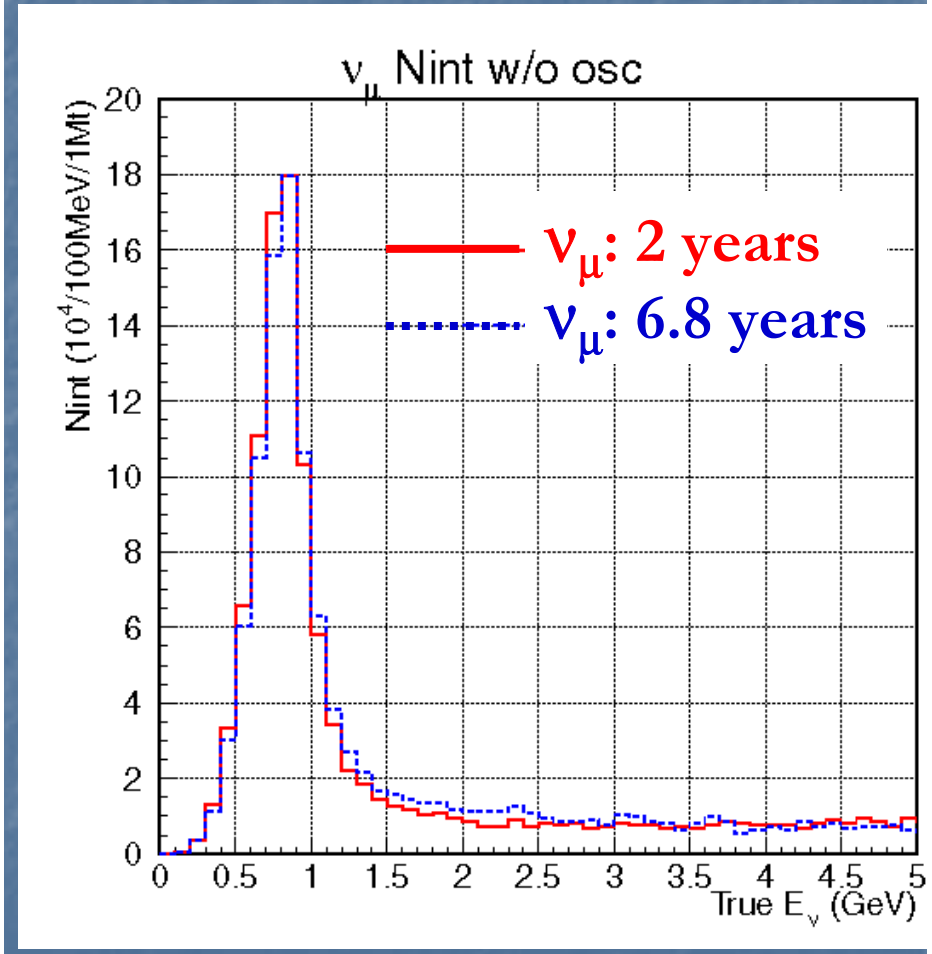
Sensitivity for θ_{13}



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

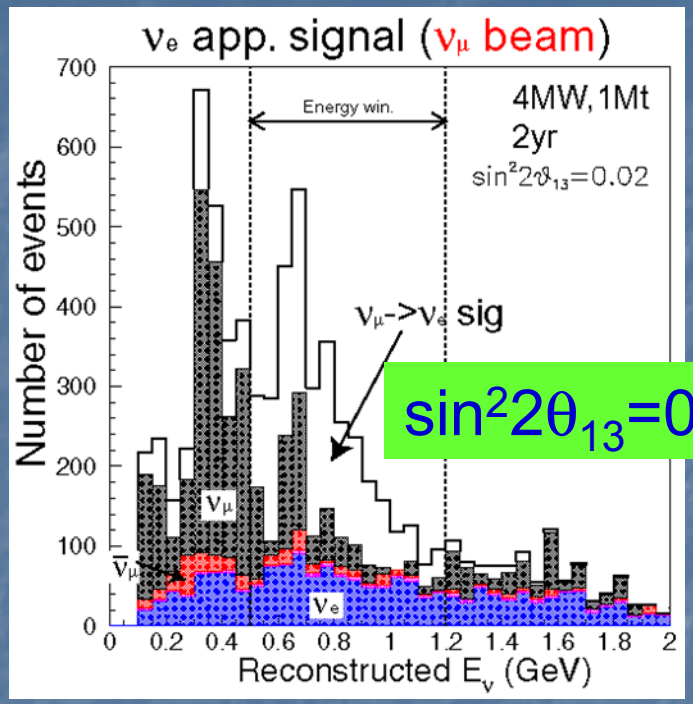
ν / ν̄ CC interaction spectrum for CPV meas.



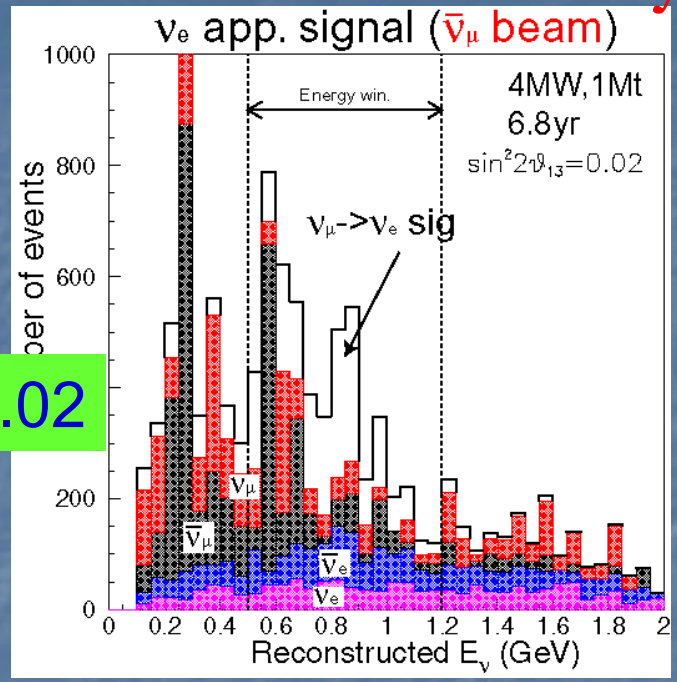


Expected signal and BG (SK full sim)

Very Preliminary



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



ν_μ:2yr, ν_μ:6.8yr
4MW
0.54Mt

$\Delta m_{21}^2=6.9\times10^{-5}\,eV^2$
$\Delta m_{32}^2=2.8\times10^{-3}\,eV^2$
$\theta_{12}=0.594$
$\theta_{23}=\pi/4$
$\theta_{13}=0.05$ ($\sin^2 2\theta_{13}=0.01$)

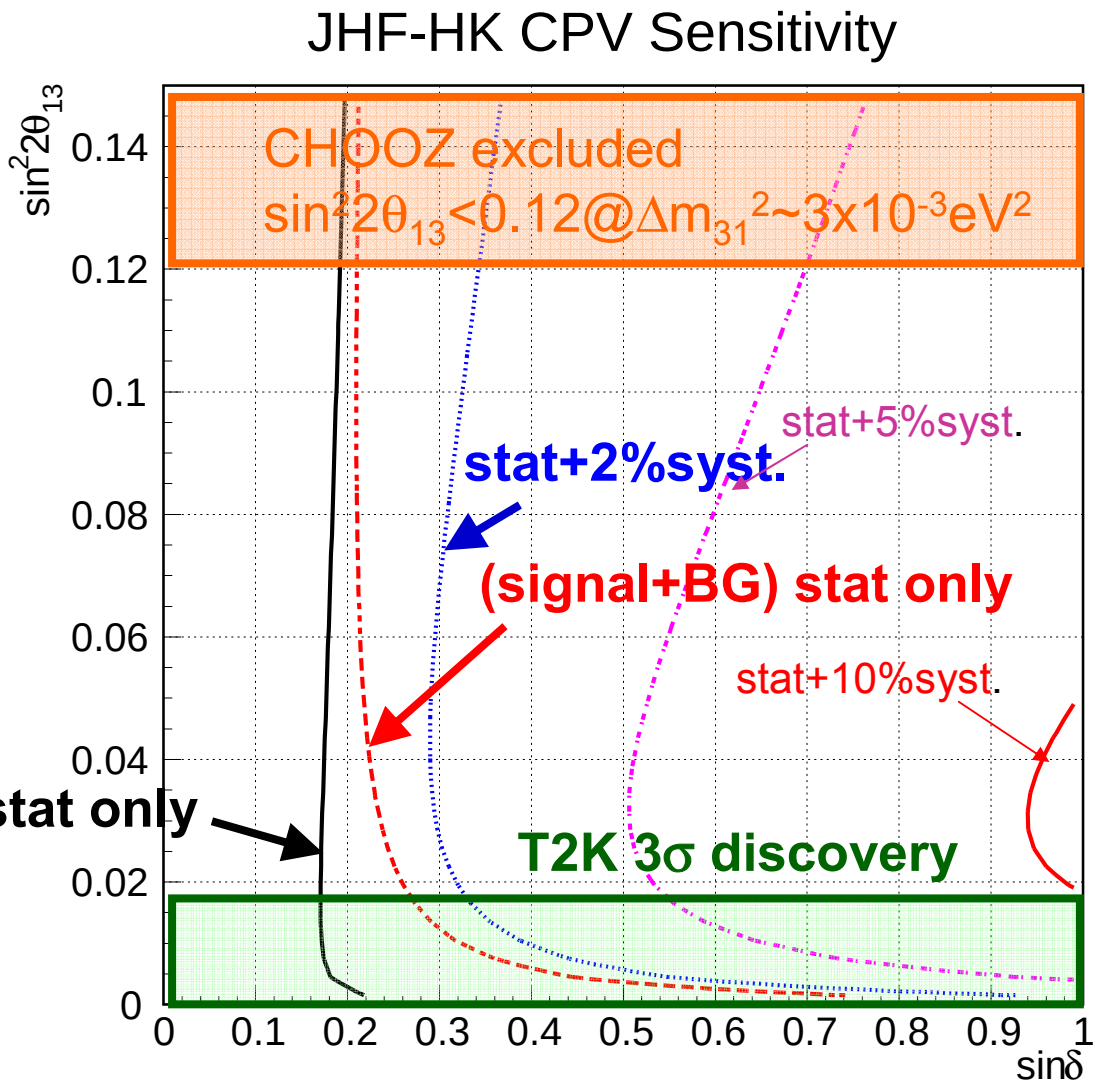
	signal		background				
	$\delta=0$	$\delta=\pi/2$	total	ν_μ	ν_μ	ν_e	ν_e
$\nu_\mu\to\nu_e$	536	229	913	370	66	450	26
$\nu_\mu\to\nu_e$	536	790	1782	399	657	297	430

Sensitivity for CPV in T2K-II

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

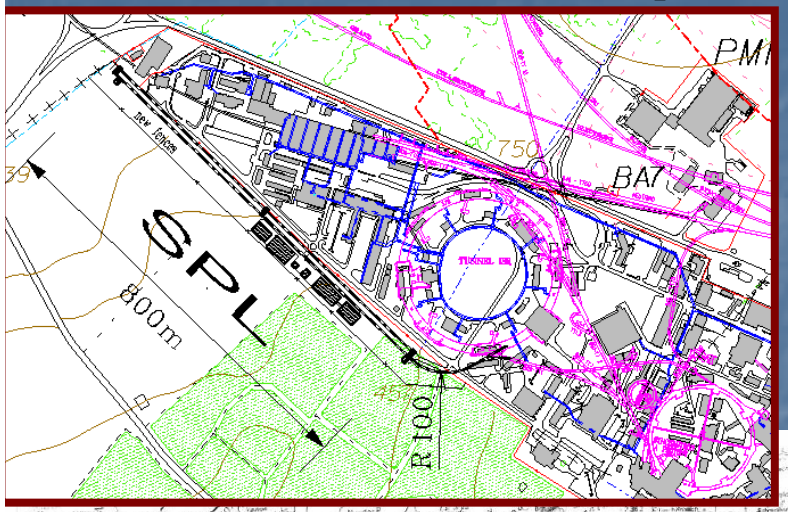
#sig ∝ $\sin^2 2\theta_{13}$

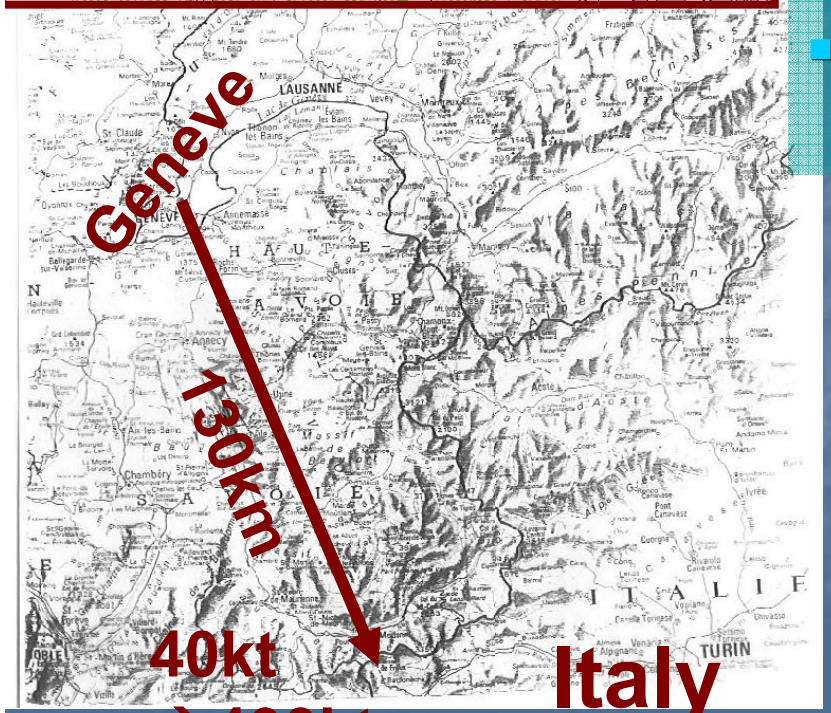
$$A_{CP} \approx \frac{\Delta m_{12}^2}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta$$



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

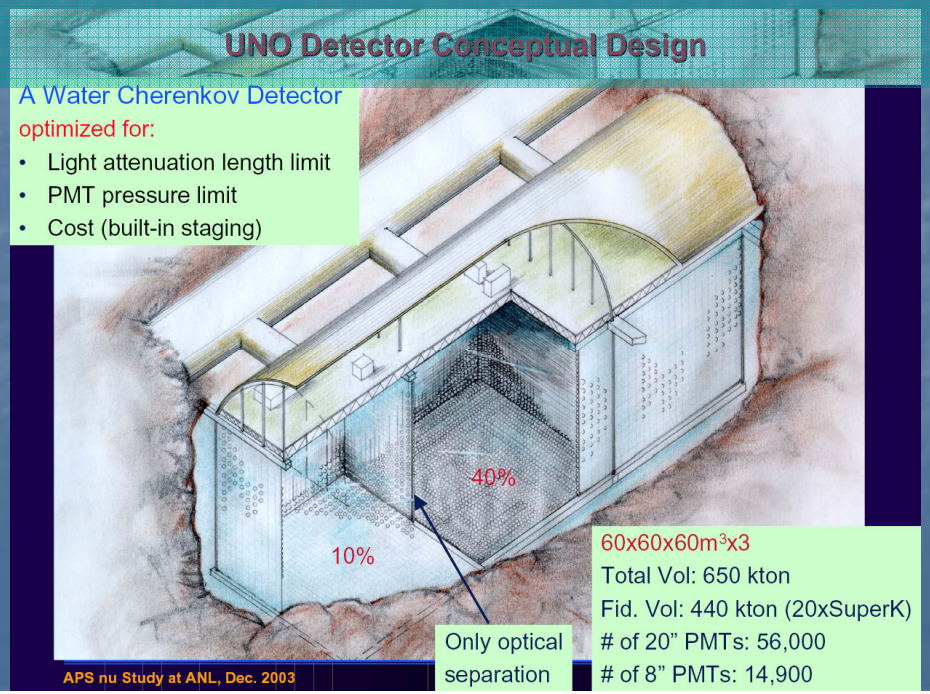
Europe: SPL→Furejus





40kt
→400kt

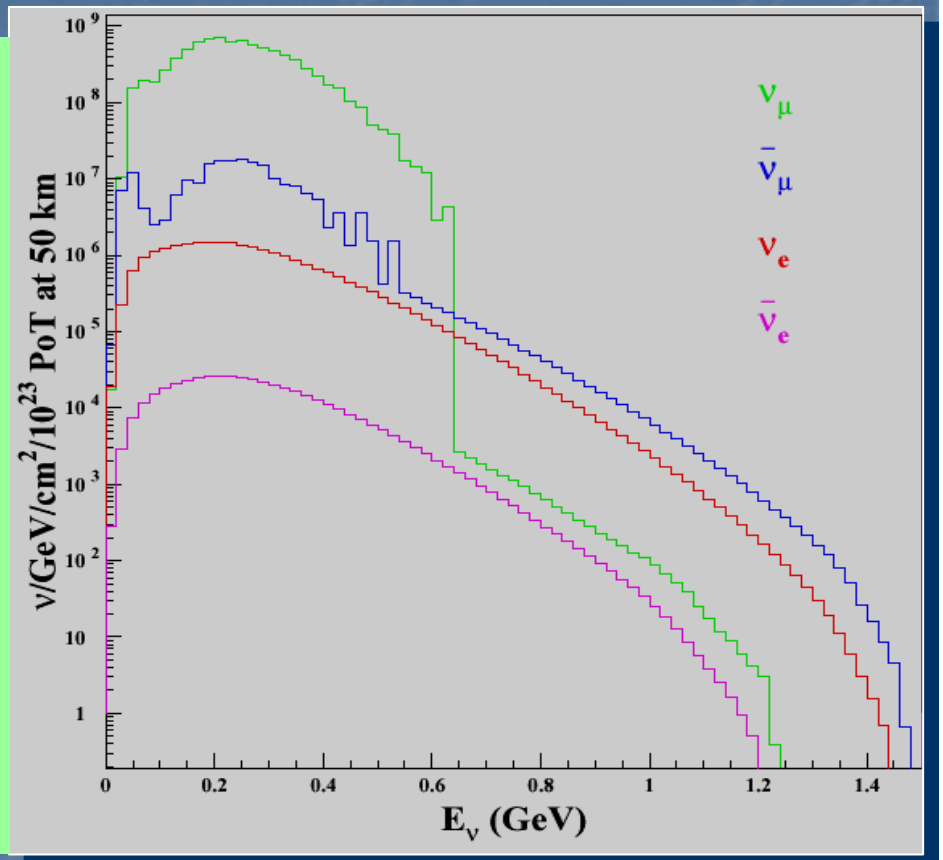
- 4MW 2.2GeV Superconducting Proton Linac (SPL) @ CERN
- Low energy wide band (Eν~0.3GeV)
- L=130km
- Water Cherenkov 40→ 400kt (UNO)
- ~18,000 νμ CC/year
- θ_{13}, CPV
- Small matter effect
- SPL in R&D, UNO in conceptual design



Fluxes for SPL beam

Flux intensities at 50 km from the target

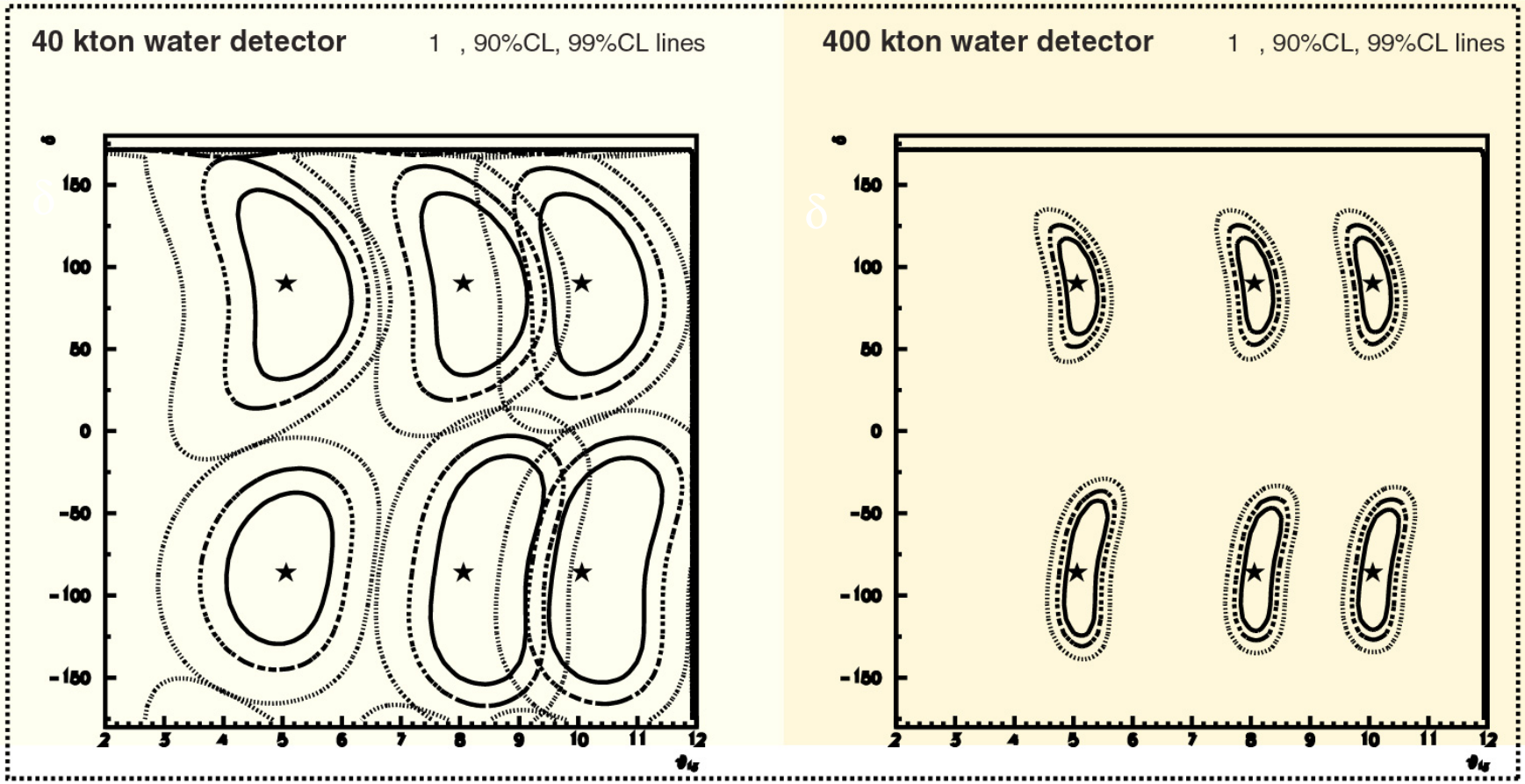
Flavour	Absolute Flux (/ 10^{23}pot/ m^2)	Rel. Flux (%)	E (GeV)
μ	$3.2 \cdot 10^{12}$	100	0.27
$\bar{\mu}$	$2.2 \cdot 10^{10}$	1.6	0.28
e	$5.2 \cdot 10^{9}$	0.67	0.32
$\bar{e}$	$1.2 \cdot 10^{8}$	0.004	0.29



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

Sensitivity for CPV

Preliminary CP sensitivity



BNL-Homestake

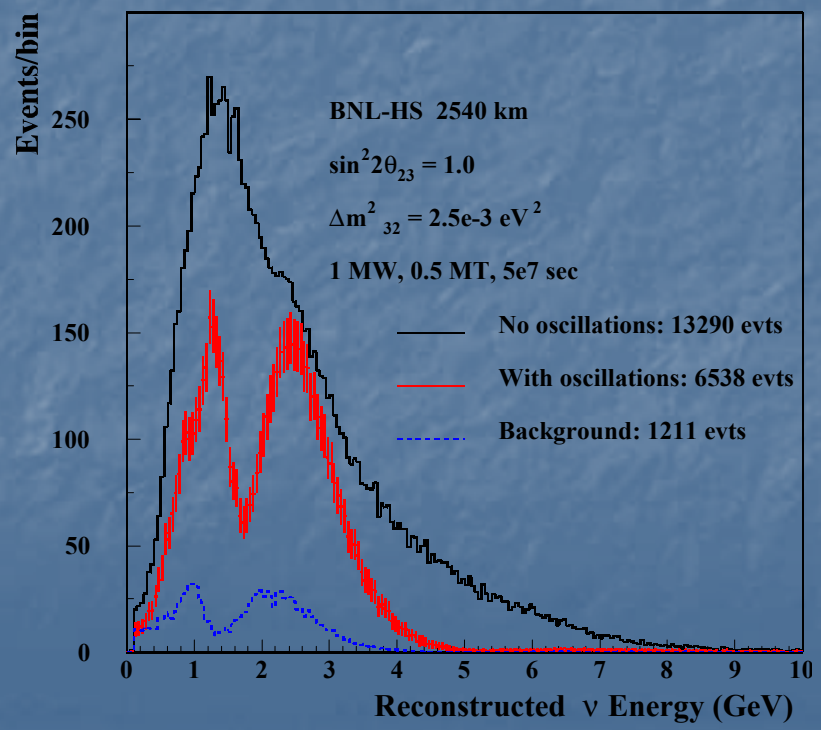
(Ref: Diwan et al., PRD68, 012002, 2003)

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

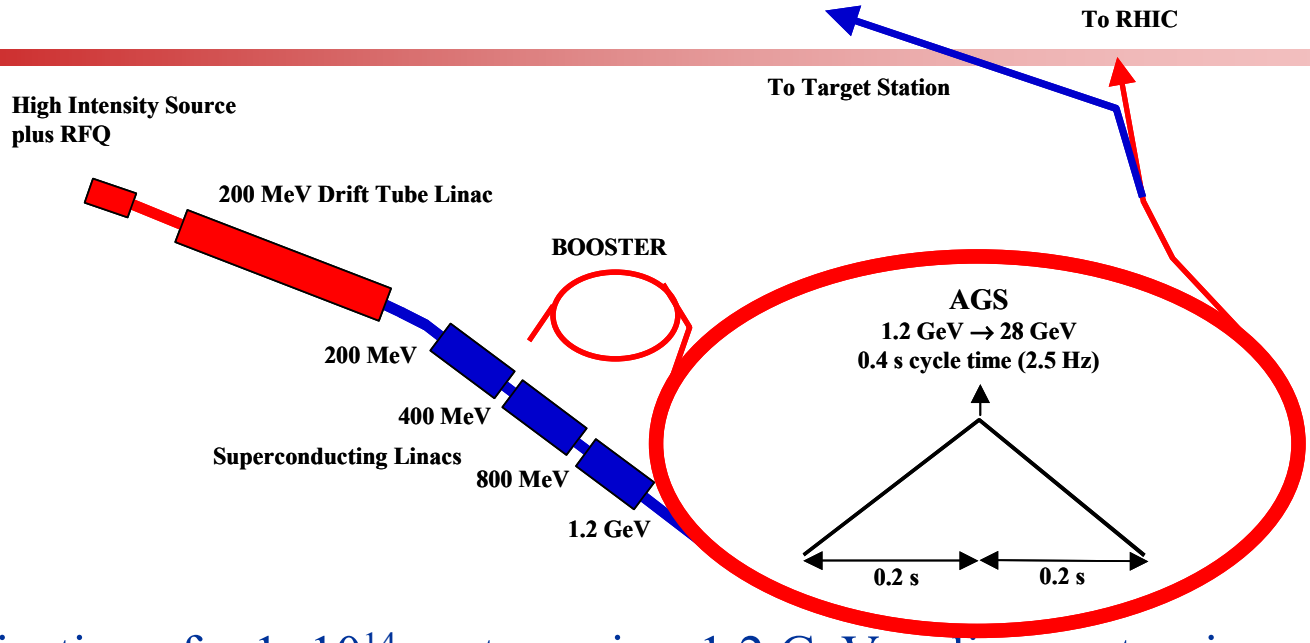
Goals

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

Possible w/ only ν run at certain parameter region

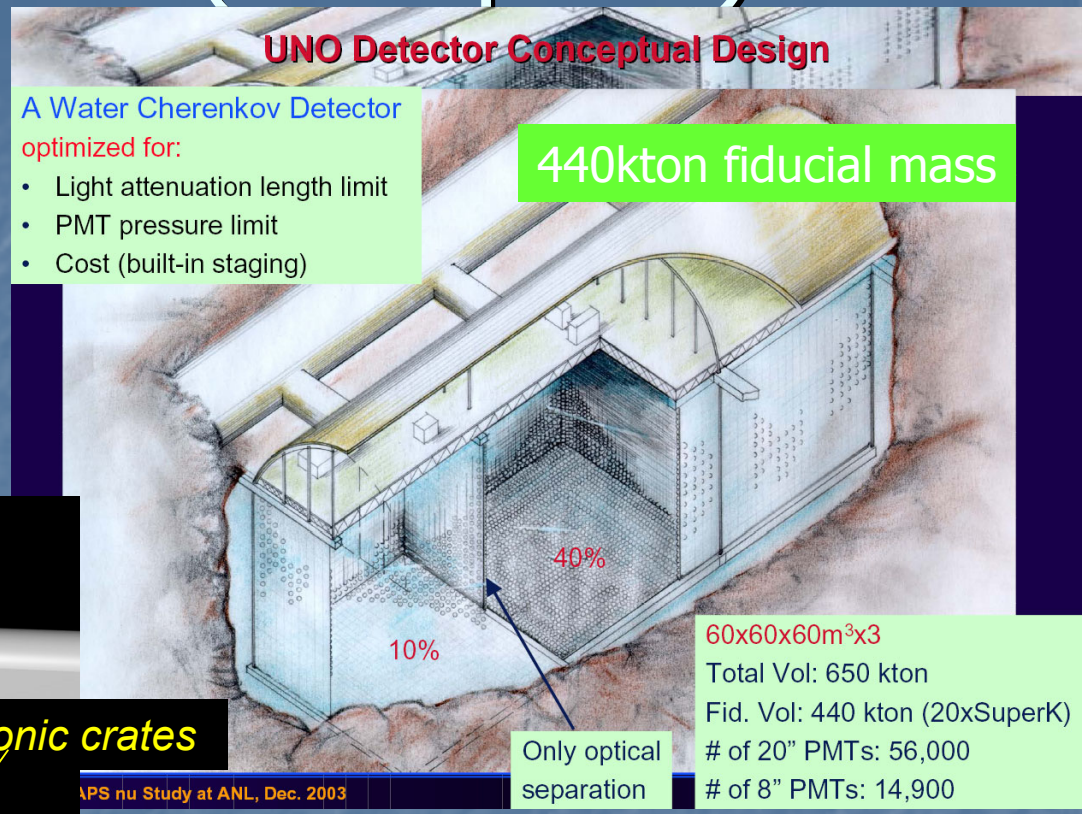


Brookhaven AGS Upgrade

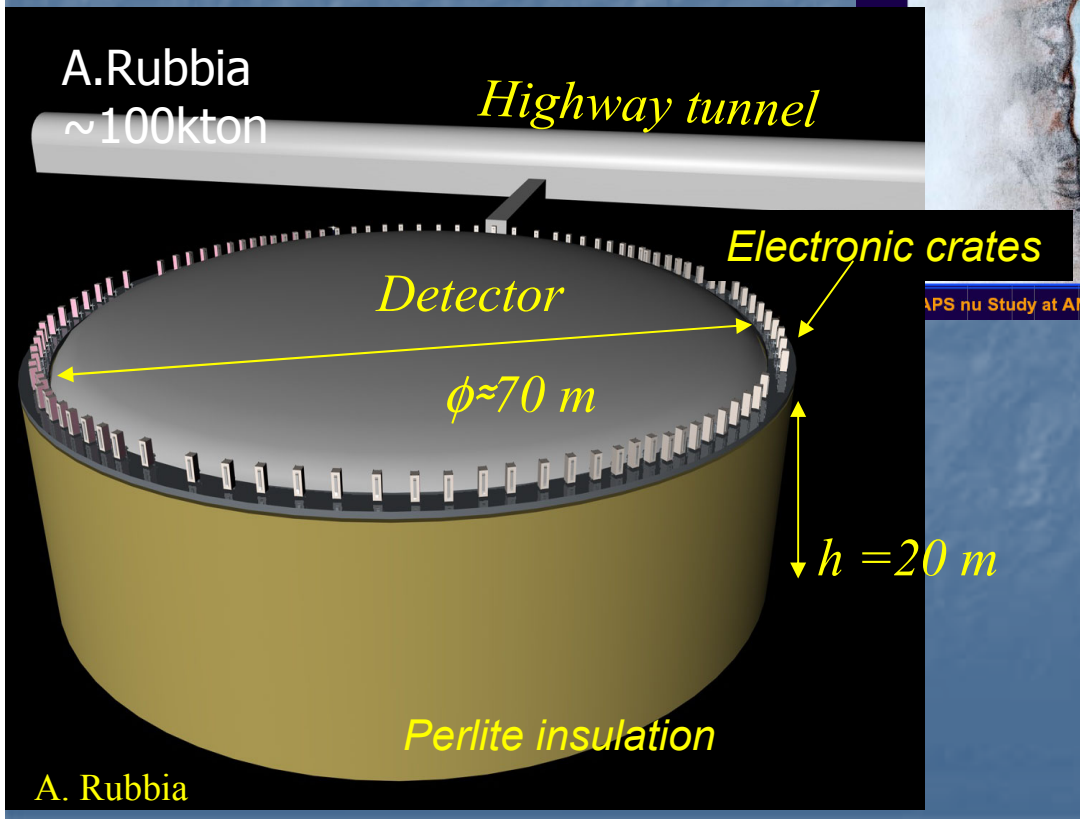


- Direct injection of ~ 1×10^{14} protons via a 1.2 GeV sc linac extension
  - low beam loss at injection; high repetition rate possible
  - further upgrade to 1.5 GeV and 2×10^{14} protons per pulse possible (x 2)
- 2.5 Hz AGS repetition rate
  - triple existing main magnet power supply and magnet current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

Detector: UNO (or Liq. Ar?)

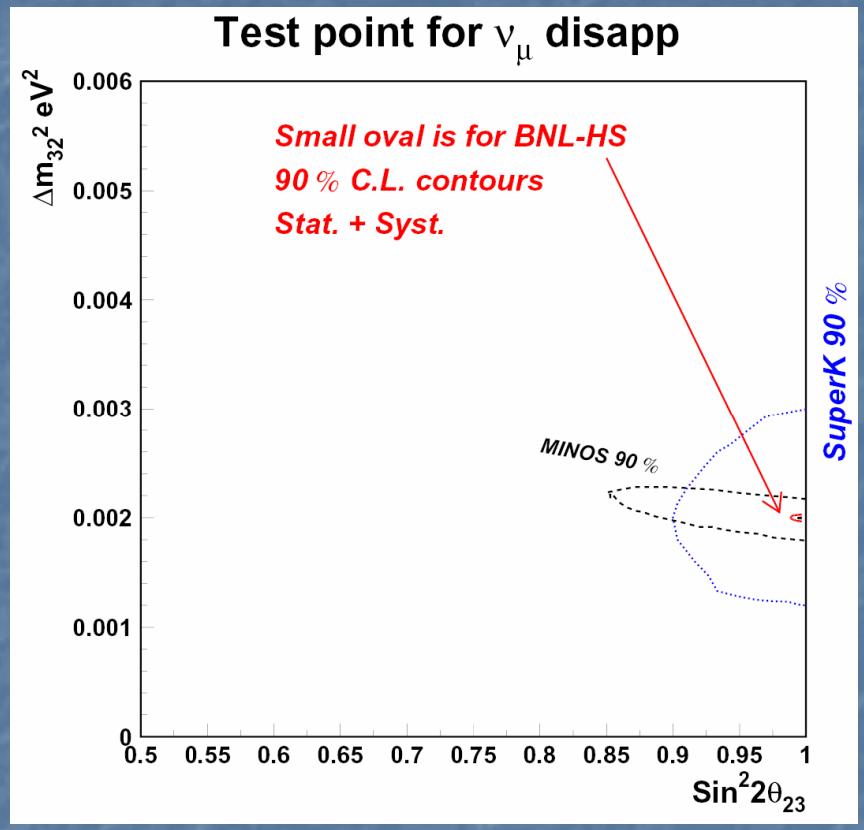


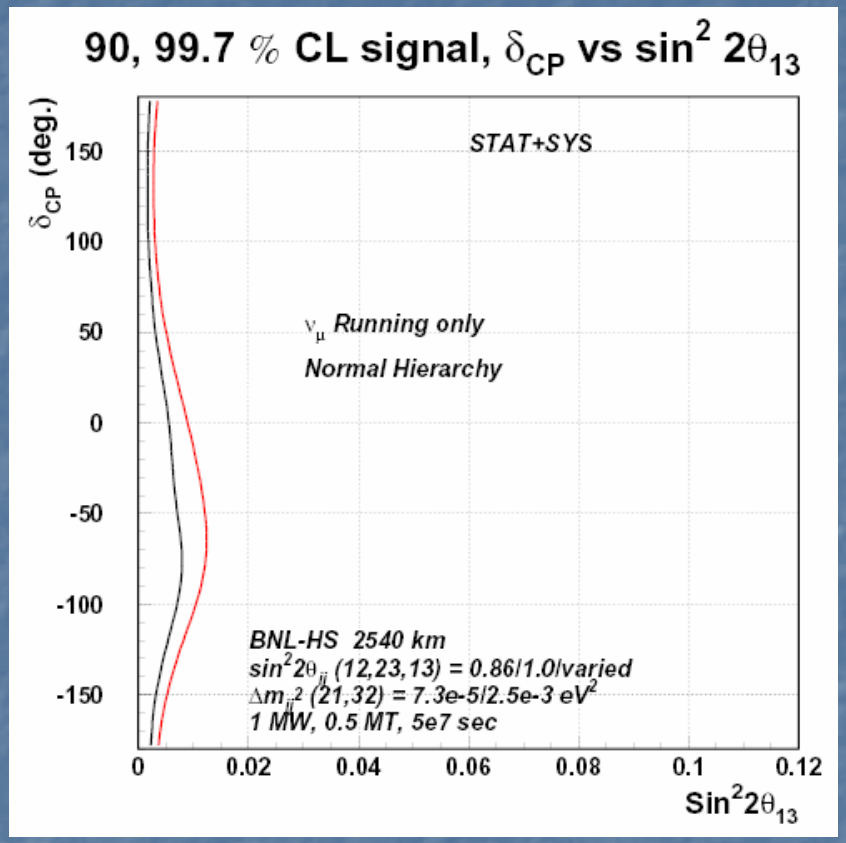
C.K.Jung



A. Rubbia

Sensitivities for disapp. & app.

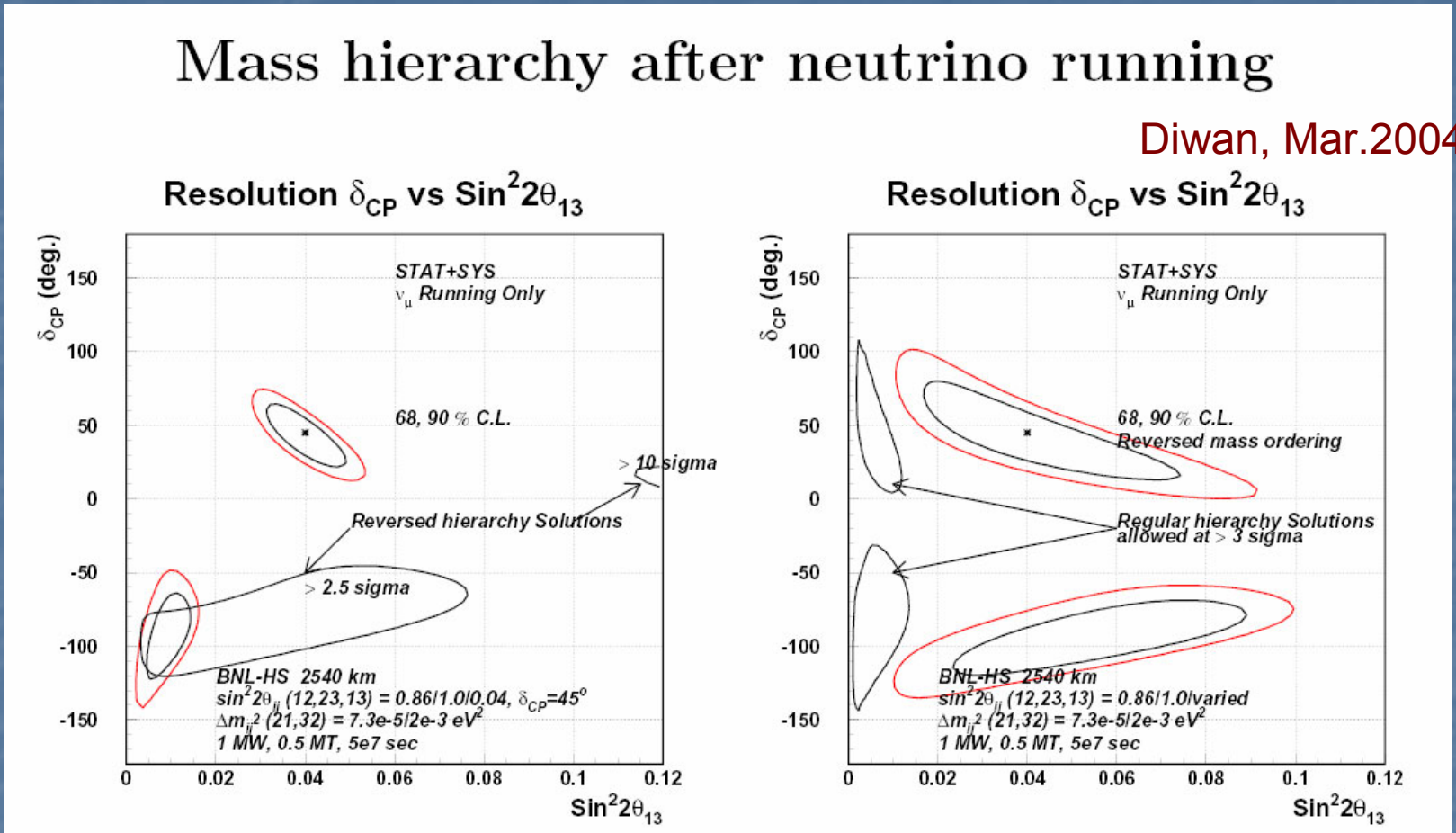




$\sin^2 2\theta$ & Δm^2 ~ 1% level

Diwan, Mar.2004

Mass Hierarchy Resolution

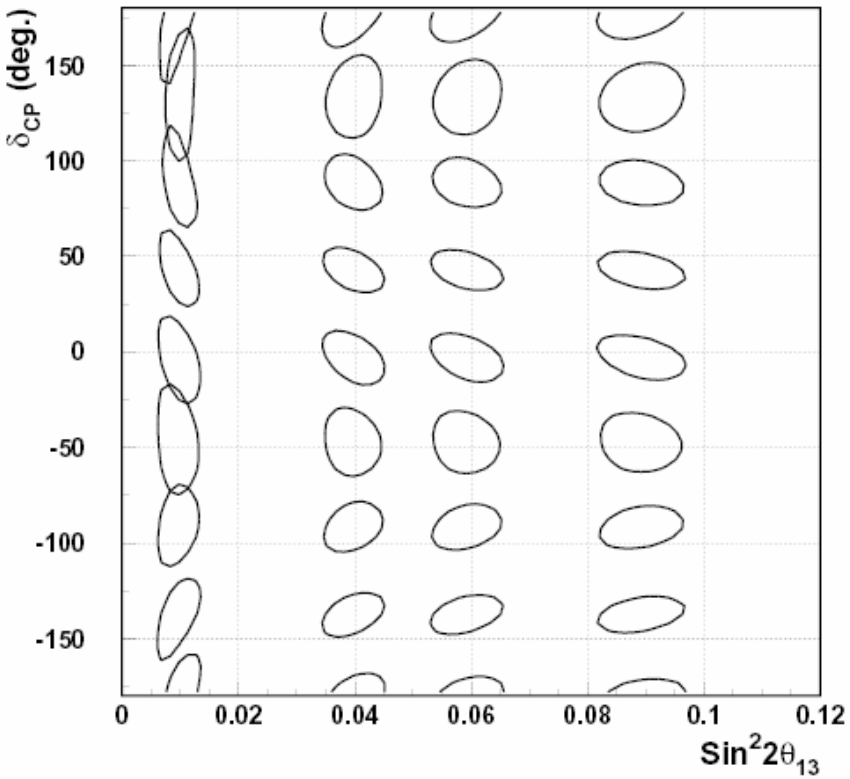


- w/ only ν running, reversed hierarchy rejected >2.5σ level
- with w/ $\nu/\bar{\nu}$ running, then >10σ

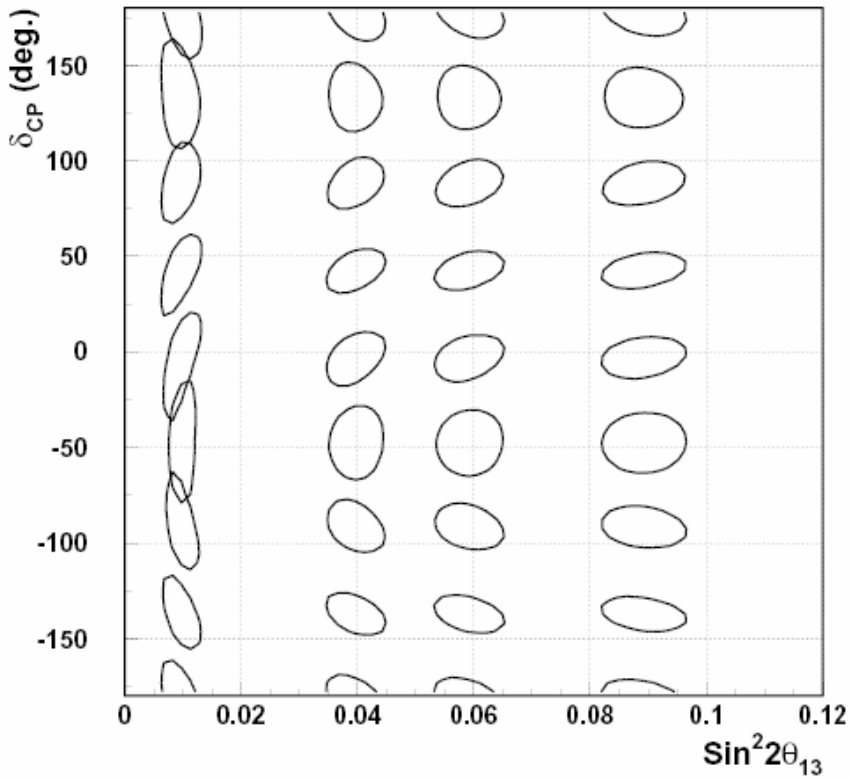
Sensitivity on CPV

CP measurement after nu and anti-nu

Regular hierarchy νυ and Antiνυ running



Reversed hierarchy νυ and Antiνυ running



Diwan, Mar.2004

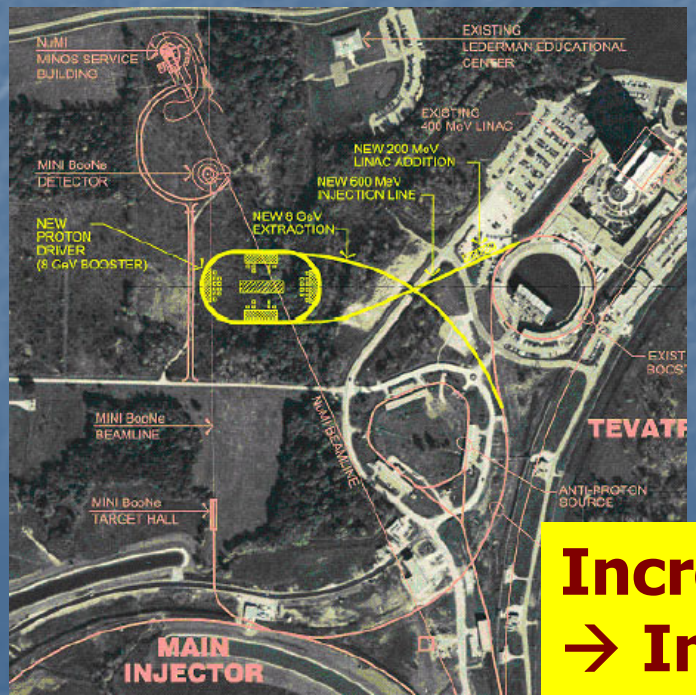
Fermilab Proton Driver (PD)

Replace injector for Main Injector

8 GeV synchrotron option

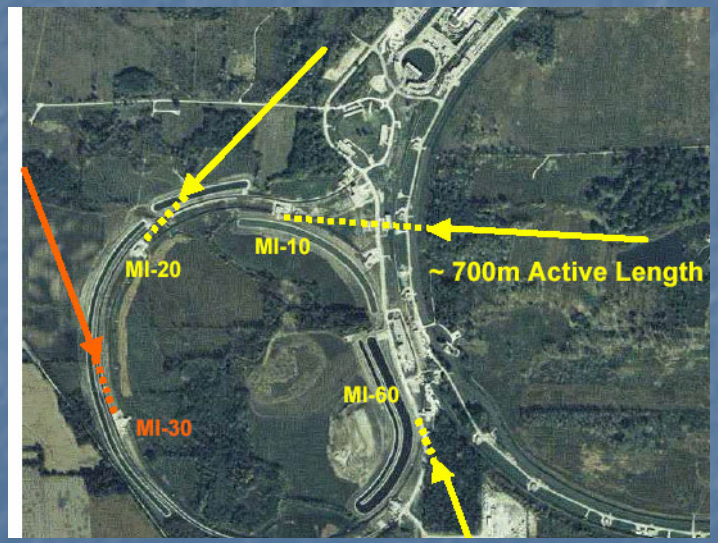
- Original concept (May 2002, Fermilab-TM-2169)
- Large aparture (100x150mm) magnets
- LINAC 400MeV → 600MeV
- MI cycle time 1.87s → 1.53s

→ Net results : MI power of 1.9MW



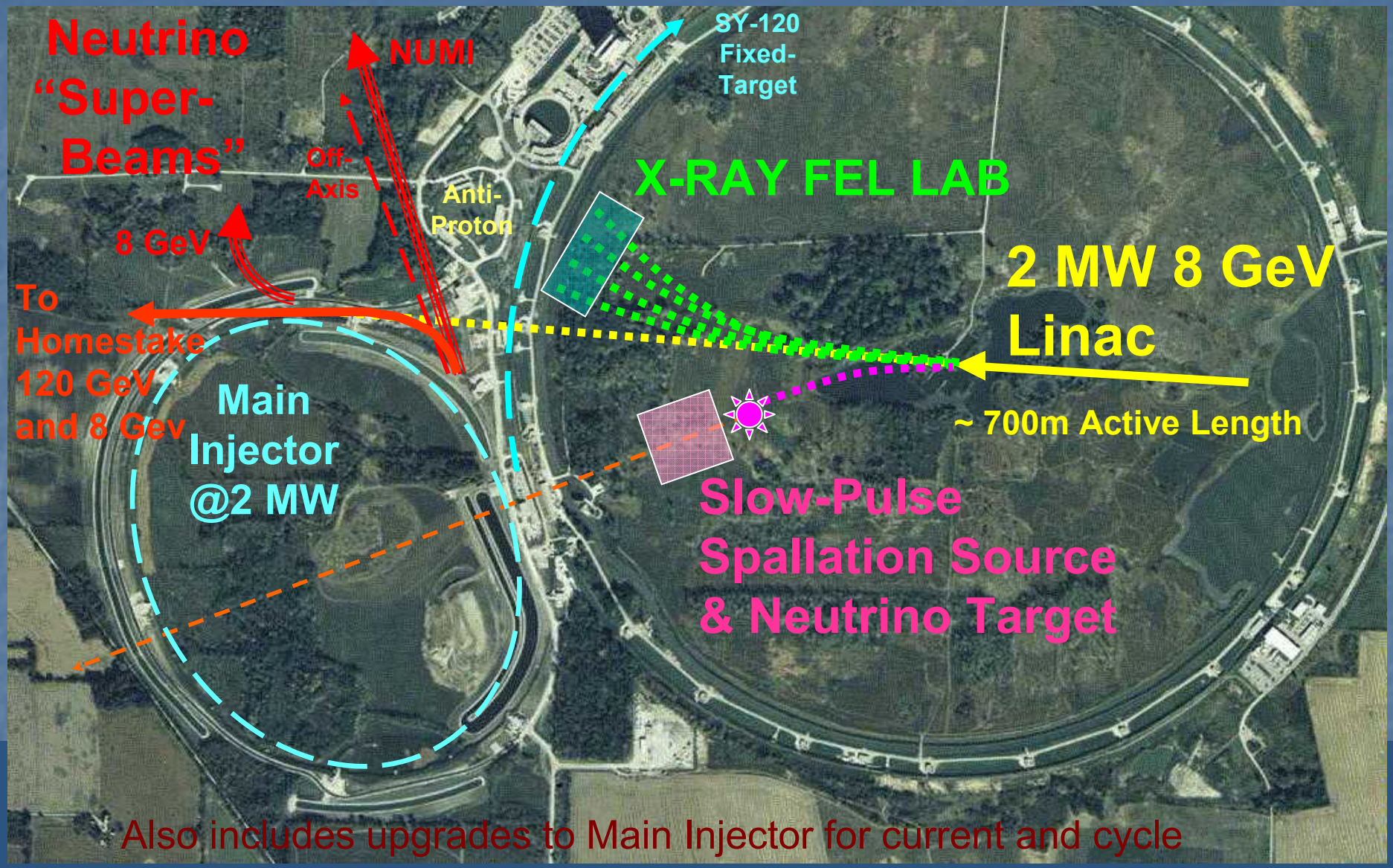
8 GeV superconducting linac

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



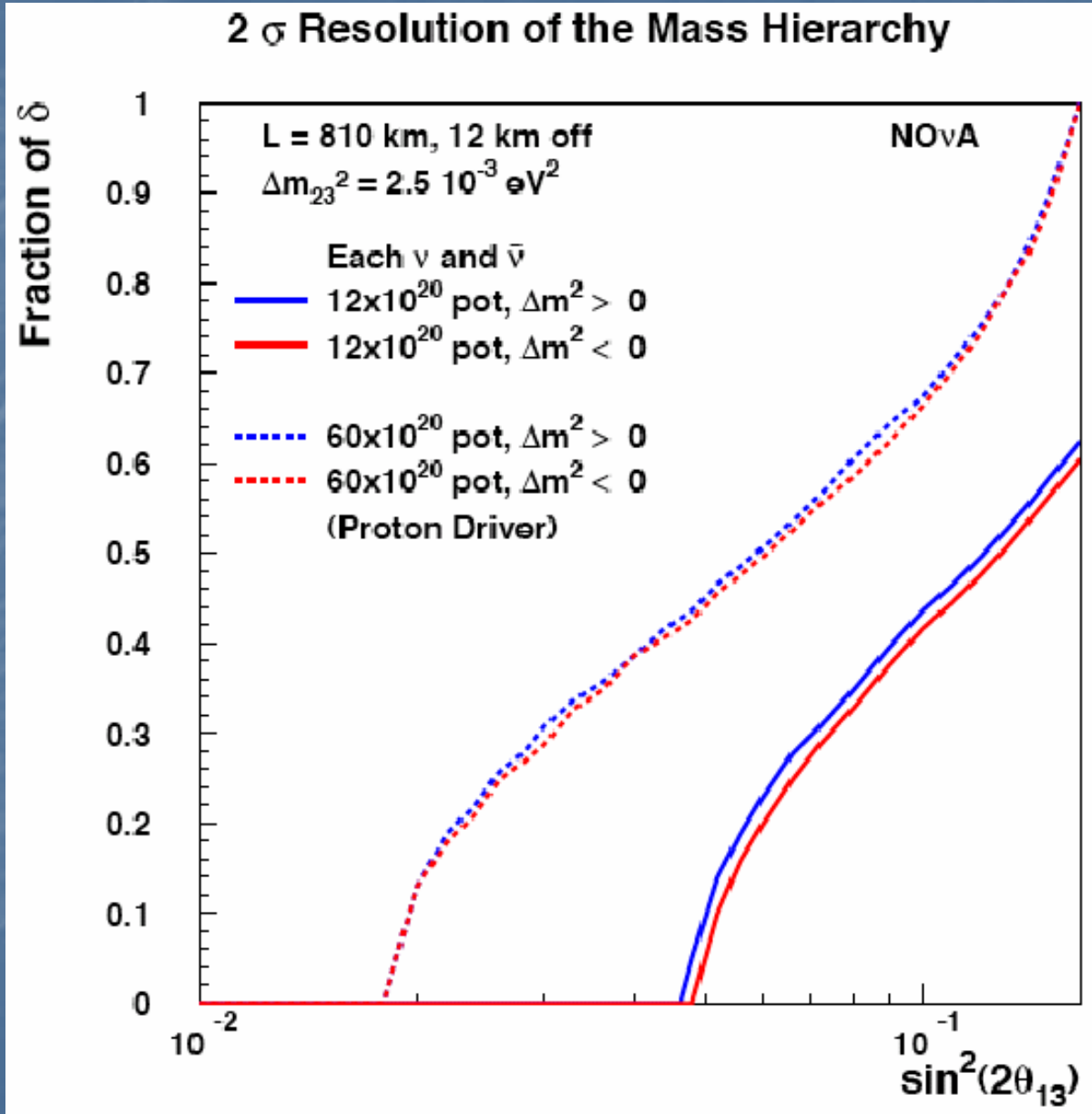
Increase MI power by x5~6 (2MW)
→ Improve MINOS & NOνA sensitivities

Potential Flexibility of LINAC



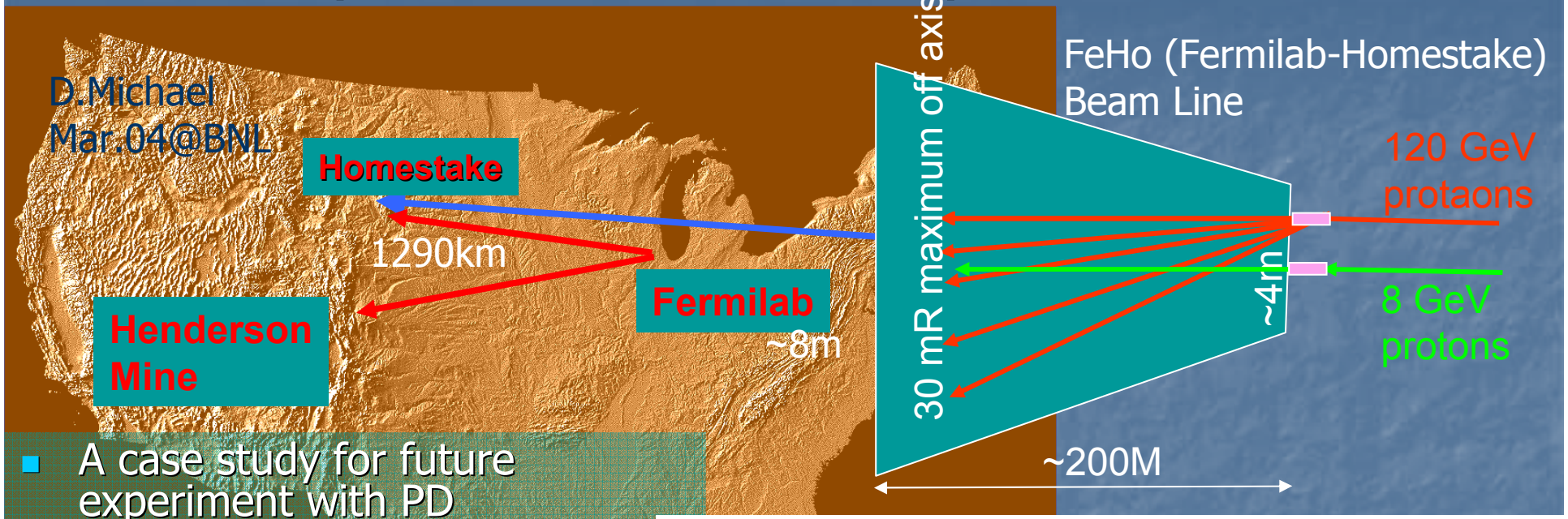
Also includes upgrades to Main Injector for current and cycle

NOνA + PD : Mass hierarchy

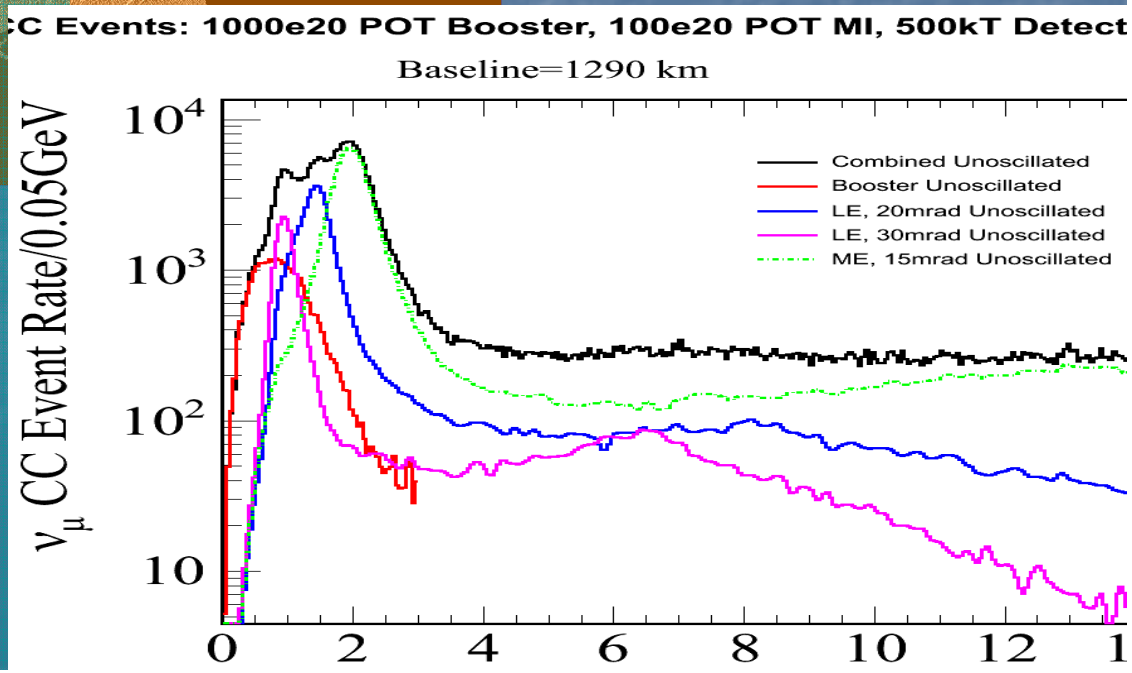


G.Feldman
Jun.04

Another possible future experiment with PD

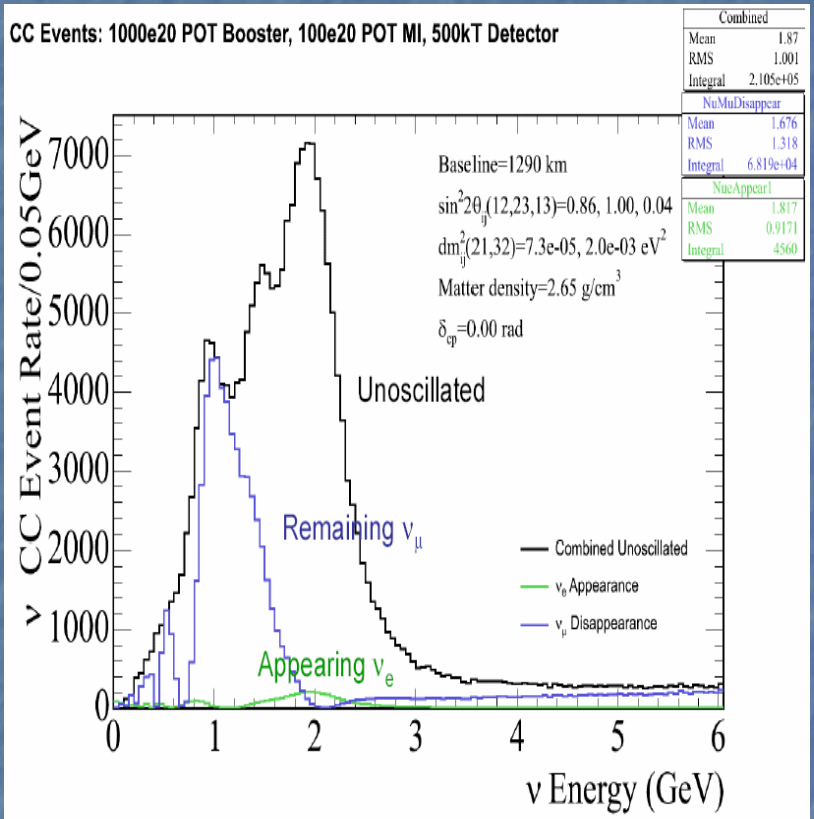


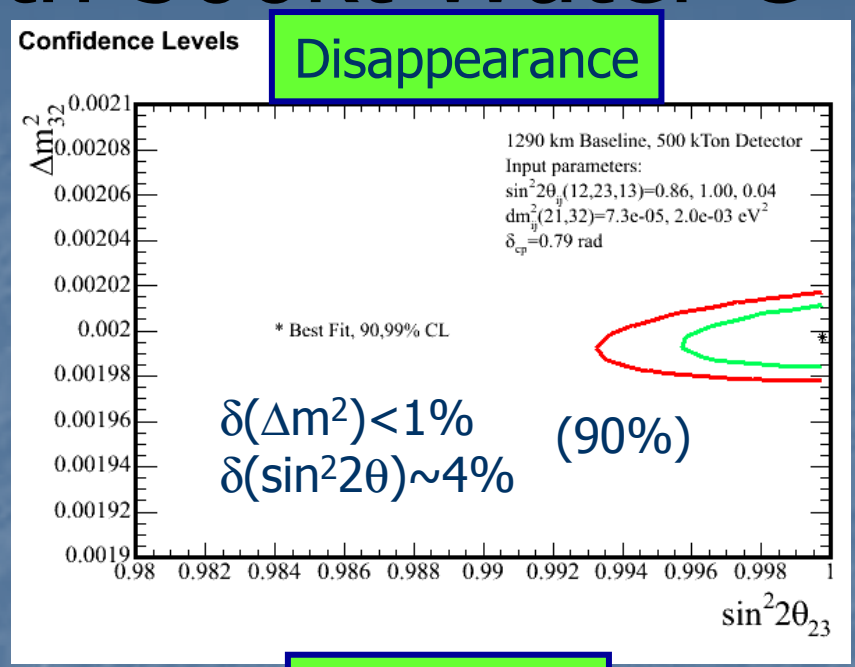
- A case study for future experiment with PD
- 2MW 8/120GeV PD→ "4MW"
- WB/OA to Homestake @1290km
- Eν=0.5~3GeV
- Cover higher osc max
- 500kt WC or 100kt Liq.Ar
- ~50k νμ CC/year
- Studies of physics potential started

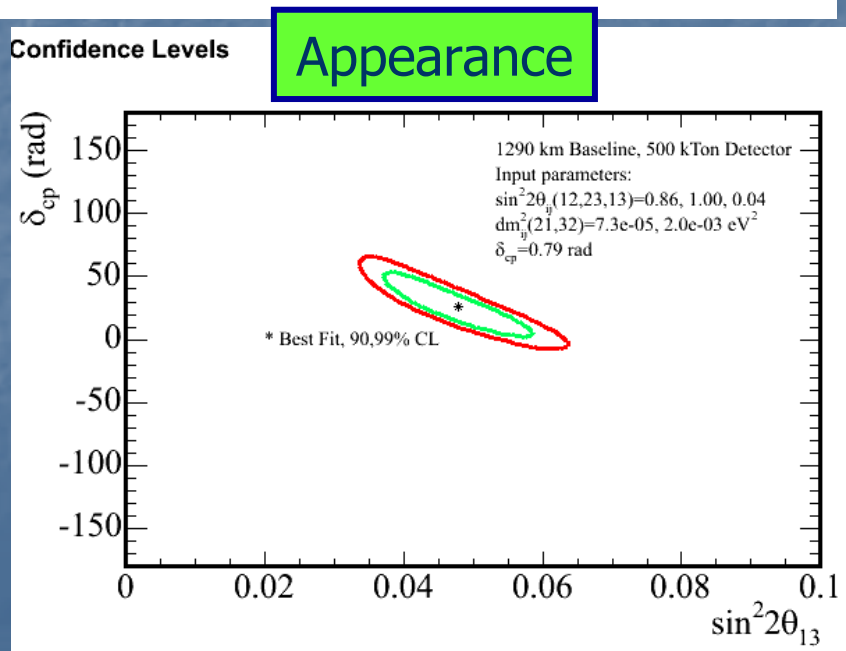


Sensitivities with 500kt Water C

D.Michael
May 04, FNAL







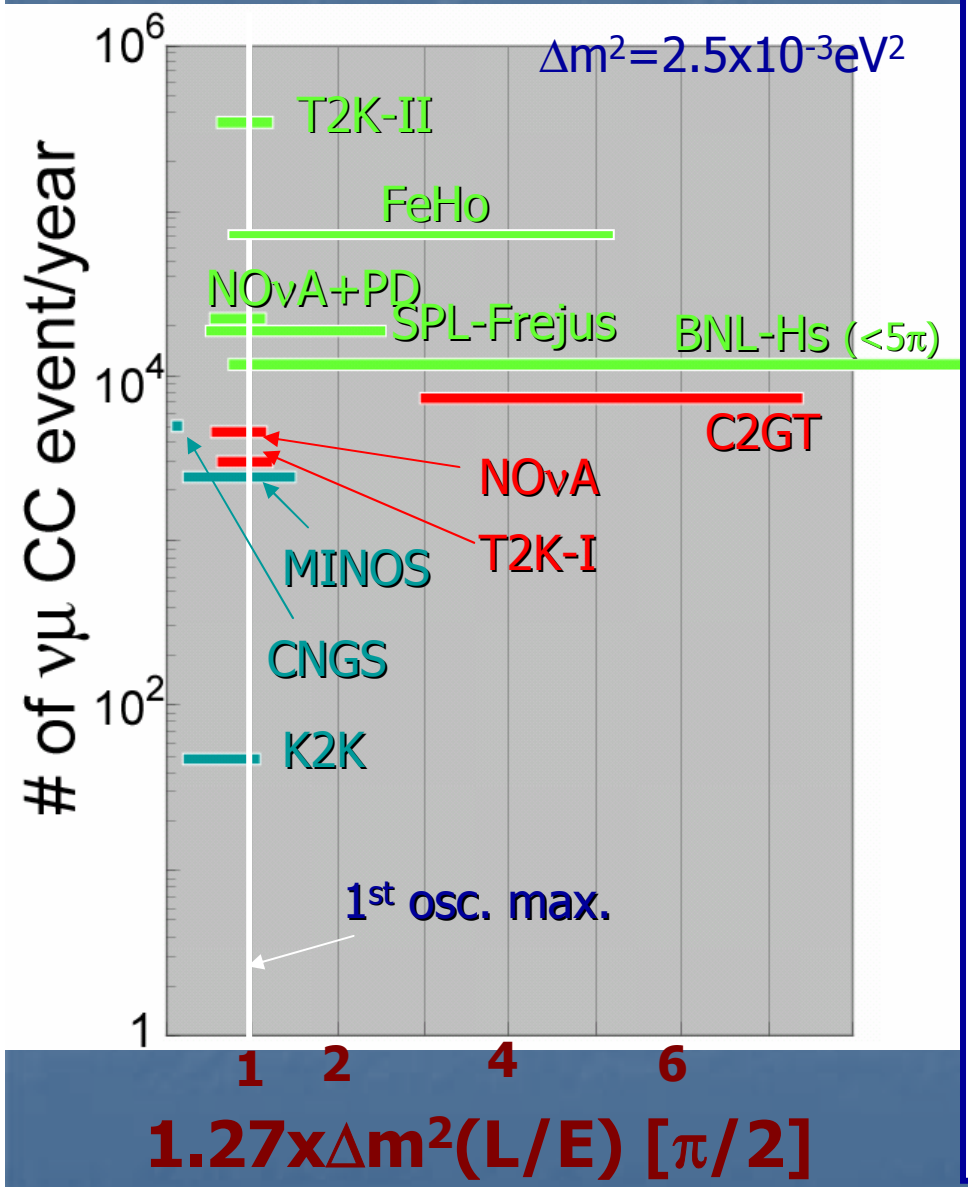
100kt Liq Ar could be better
thanks to det. resolution
Study to be done

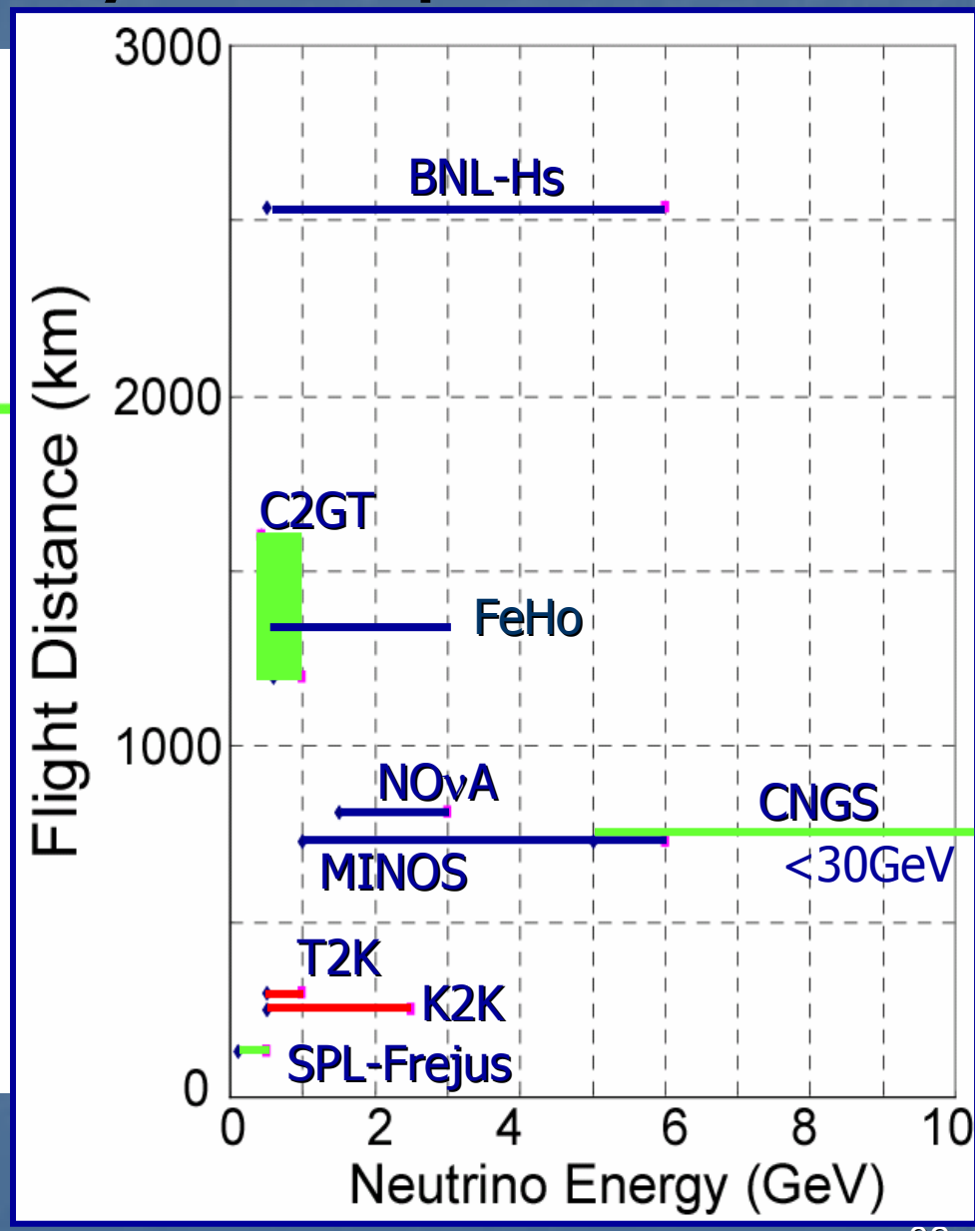
Summary of ("super-beam") LBL experiments

	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%	I
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%	I
T2K-I	50	0.75	OA	0.7	295	22.5	~3,000	0.2%	II
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%	II
T2K-II	50	4	OA	0.7	295	~500	~360,000	0.2%	III
NOνA+PD	120	2	OA	~2	810?	50?	~23,000	0.3%	III
BNL-Hs	28	1	WB/OA	~1	2540	~500	~13,000		III
SPL-Furejus	2.2	4	WB	0.32	130	~500	~18,000	0.4%	III
FeHo	8/120	"4"	WB/OA	1~3	1290	~500	~50,000		III

Running, constructing or approved experiments

"Graphical" Summary of experiments

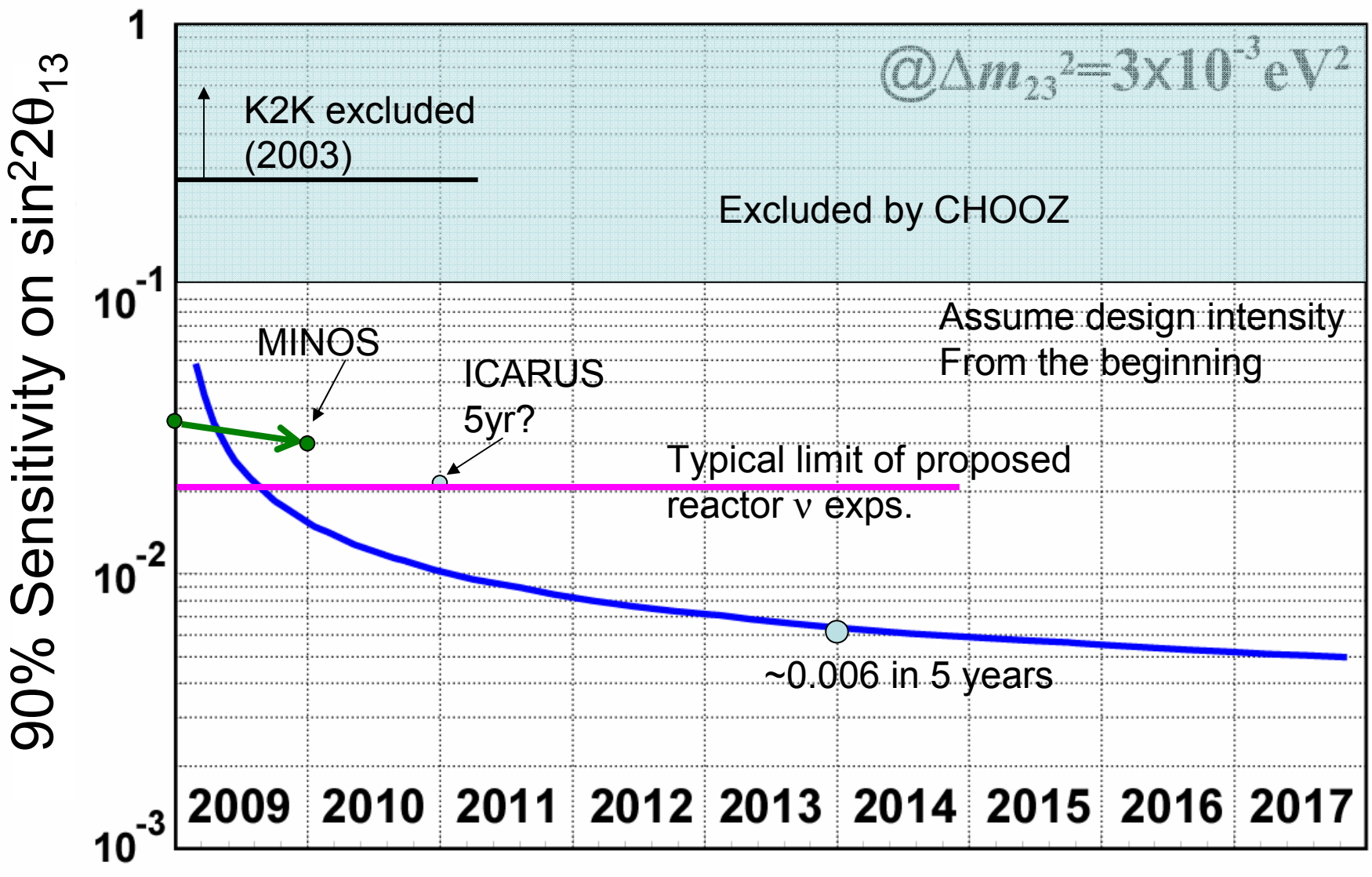




Summary

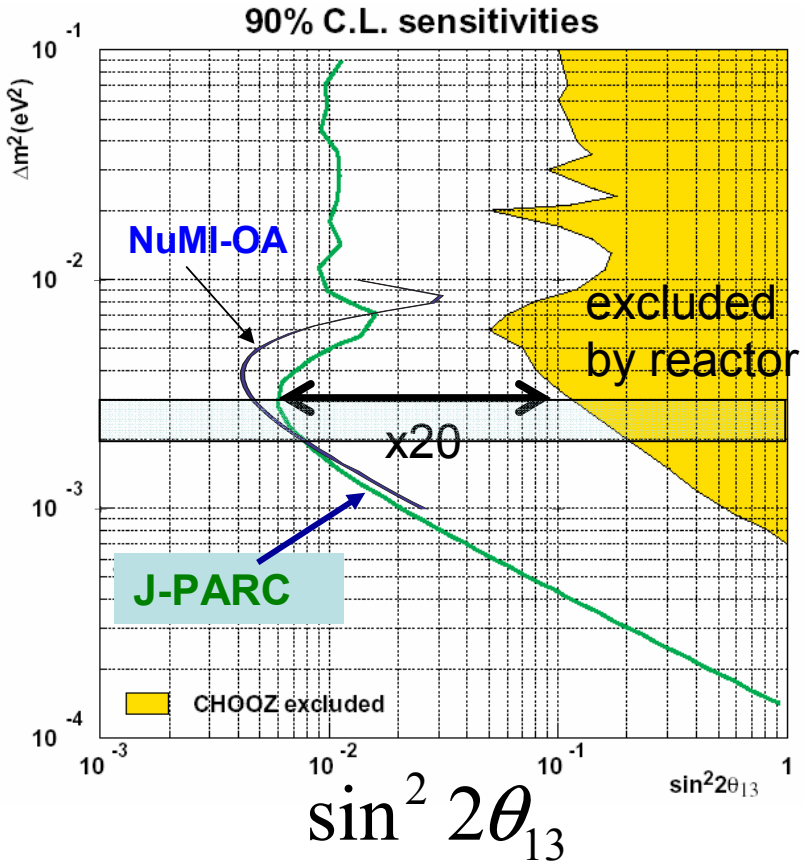
- Next generation "Super Beam" experiments provide chances to answer next important goals of ν physics
  - θ_{13}
  - CPV, sign of Δm^2, ..
- Several experiments are under consideration
  - (Multi-)MW beam + Mton detector (or Liq.Ar)
  - US(BNL, FNAL), Europe(CERN) and Japan
- Future direction much depend on results from "2nd phase" experiments
  - T2K-I(2009~) and NOνA(if approved)
  - If ν_e appearance not found ($\sin^2 2\theta_{13}<0.006$)? CPV only in νFact?
- Let's do experiment to know θ_{13} (2nd phase) ASAP!!, (while reducing too many meeting!)

Sensitivity on ν_e appearance



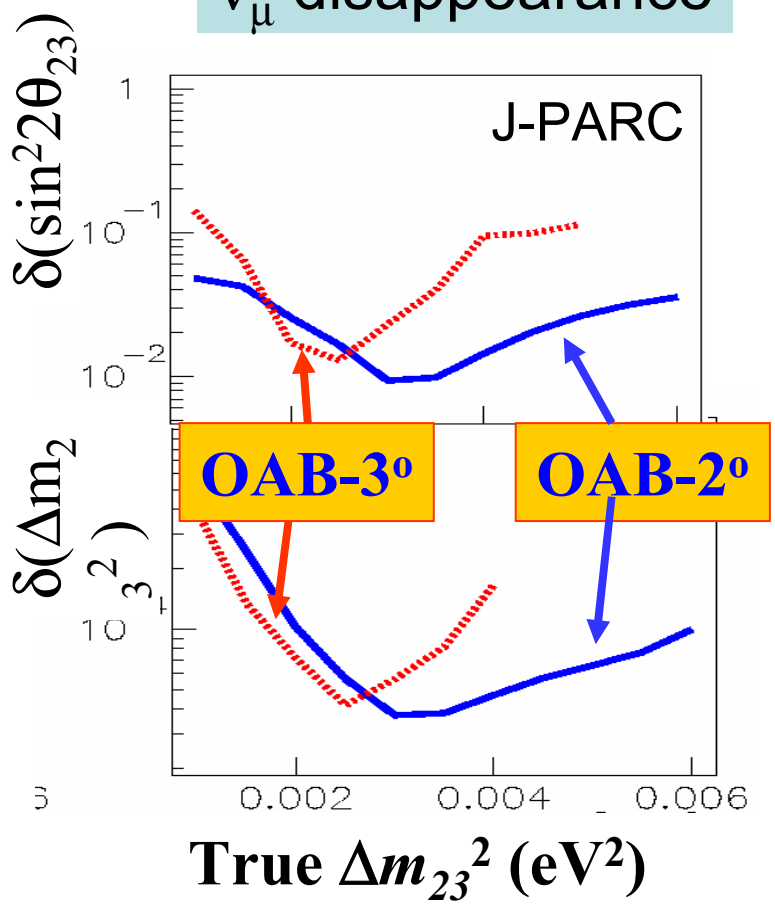
Sensitivities

Search for ν_e appearance



J-PARC1 $\sin^2 2\theta_{13}>0.006$
NuMI-OA1 $\sin^2 2\theta_{13}>0.005$

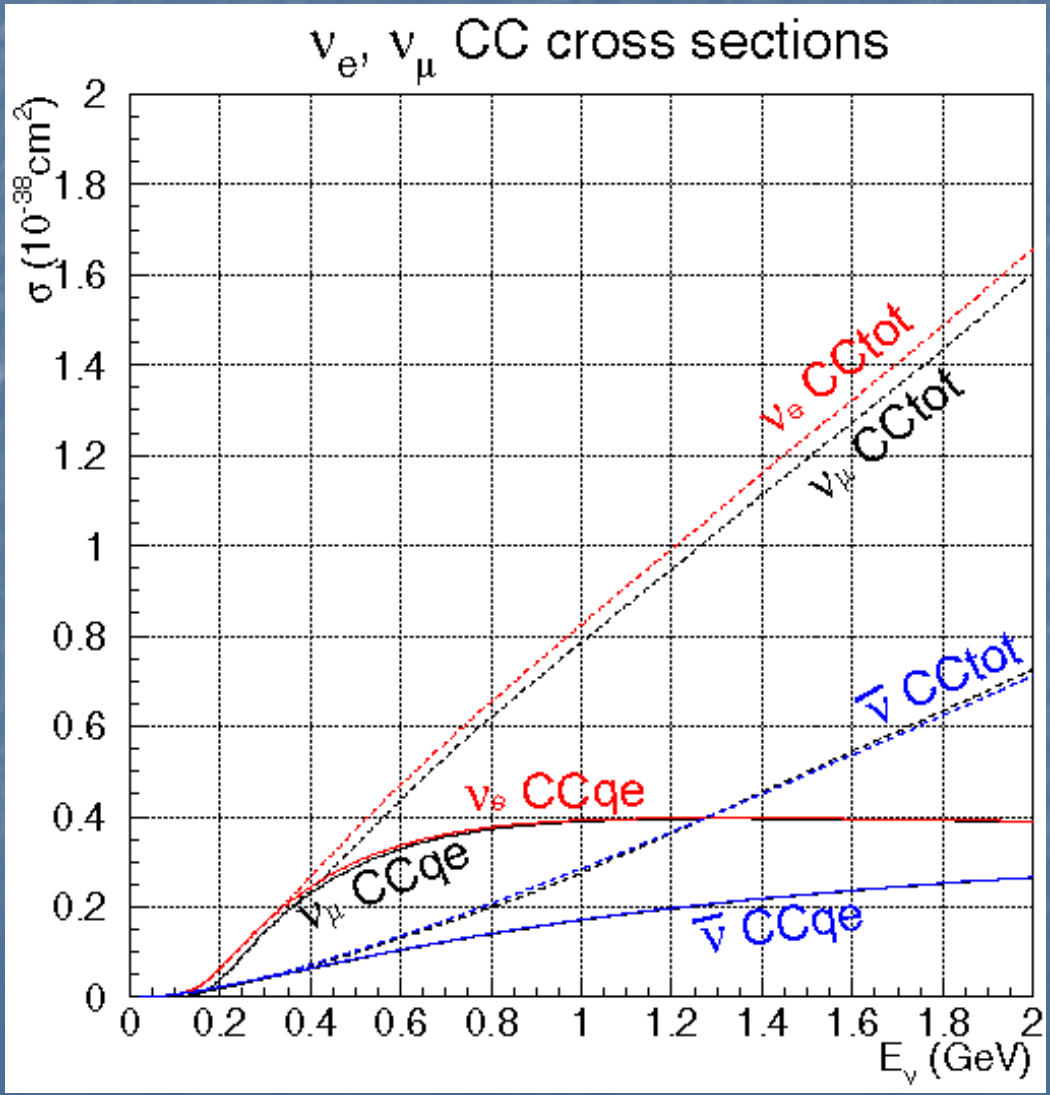
ν_μ disappearance



$\delta(\sin^2 2\theta)\sim 0.01$ in 5 years
$\delta(\Delta m^2)$ $\sim<1\times 10^{-4}$ in 5 years

J-PARC: w/ beam MC sim, & full SK det. sim.

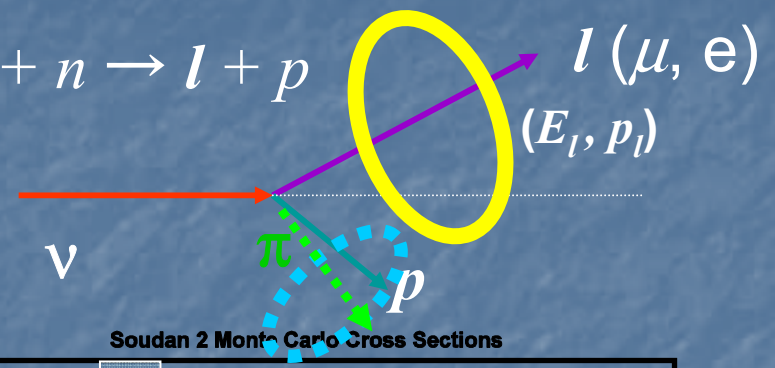
Cross sections



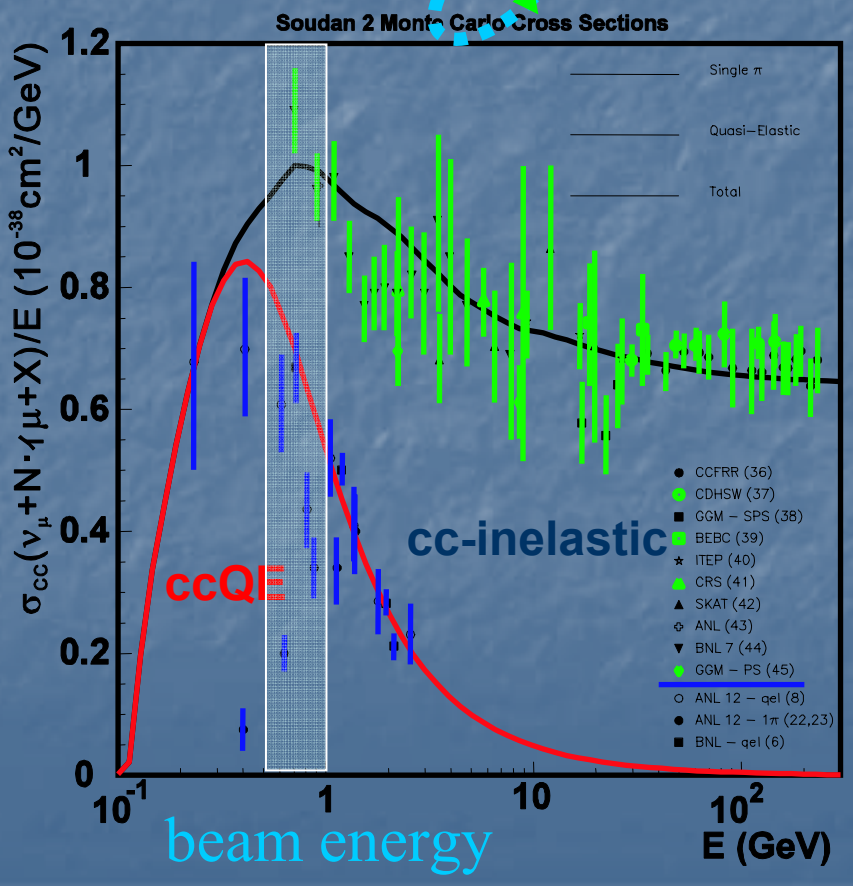
Eν reconstruction in water Cherenkov

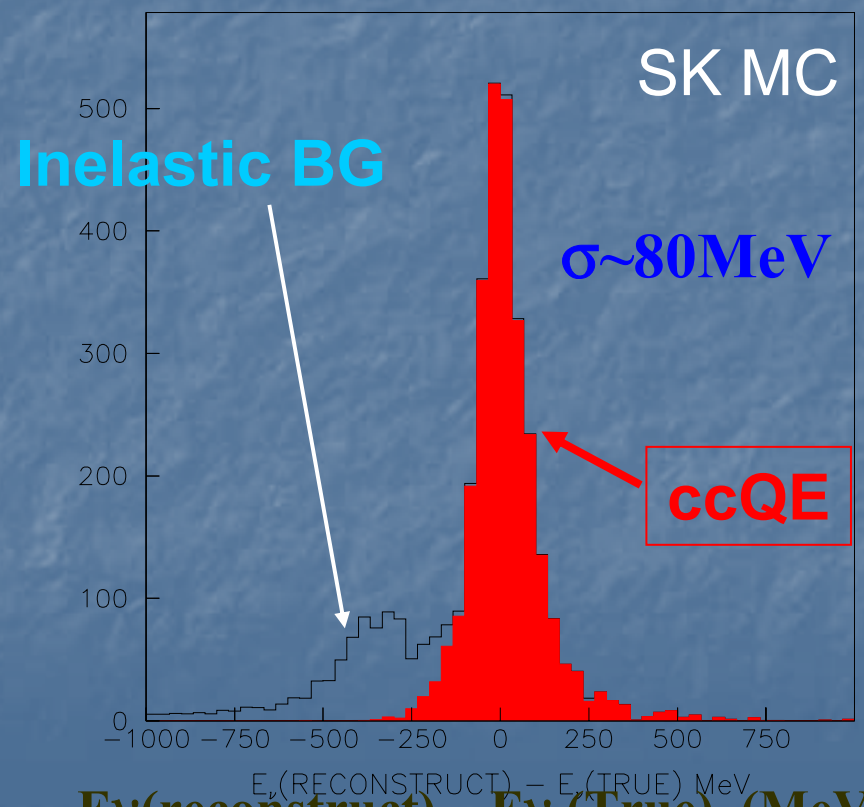
Assume CC Quasi Elastic (QE) reaction

$$\nu_\mu + n \rightarrow l + p$$



$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$





Eν(reconstruct) – Eν (True) (MeV)

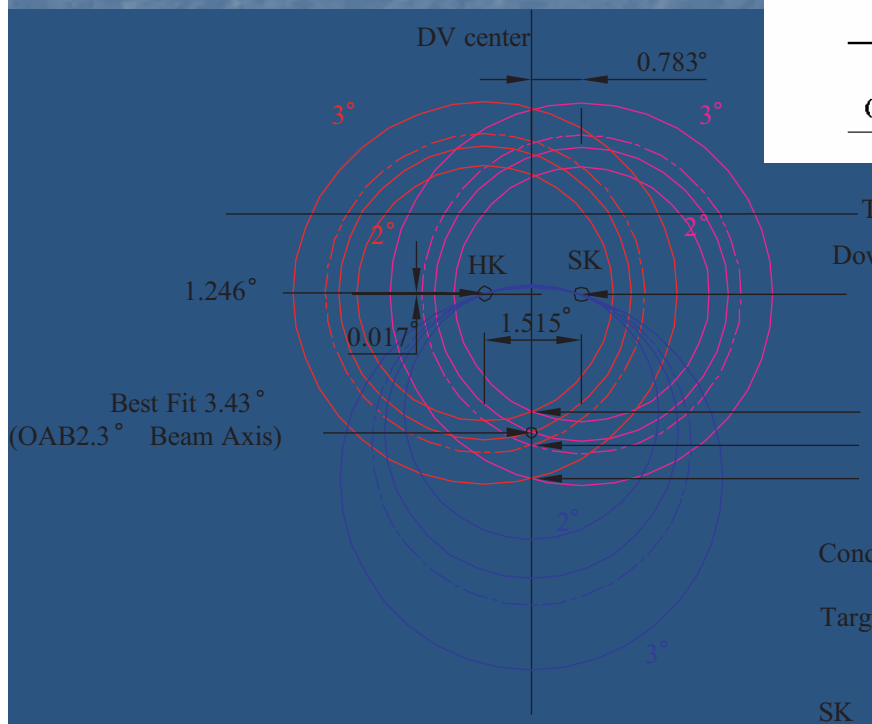
Optimization of Decay Volume

Peak Eν is determined by off-axis angle.

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

Δm^2	2.04	2.18	2.75	3.17	3.28
$[10^{-3}eV^2]$	(90% A.R.)	(80% A.R.)	(best fit)	(80% A.R)	(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



Target Level@Tokai

Downward angle
1.263° (44m@2km)

Best Fit 3.43°
(OAB2.3° Beam Axis)

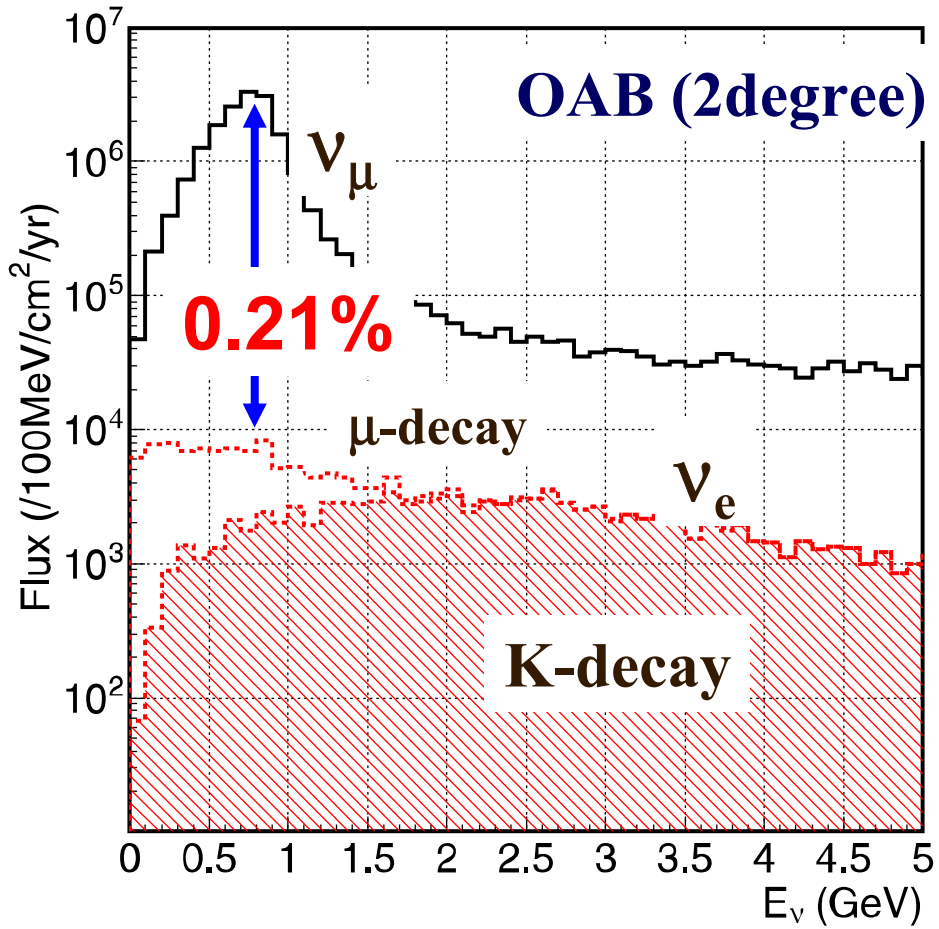
3.103° (OAB2° beam axis)
3.637° (OAB2.5°)
4.159° (OAB3°)

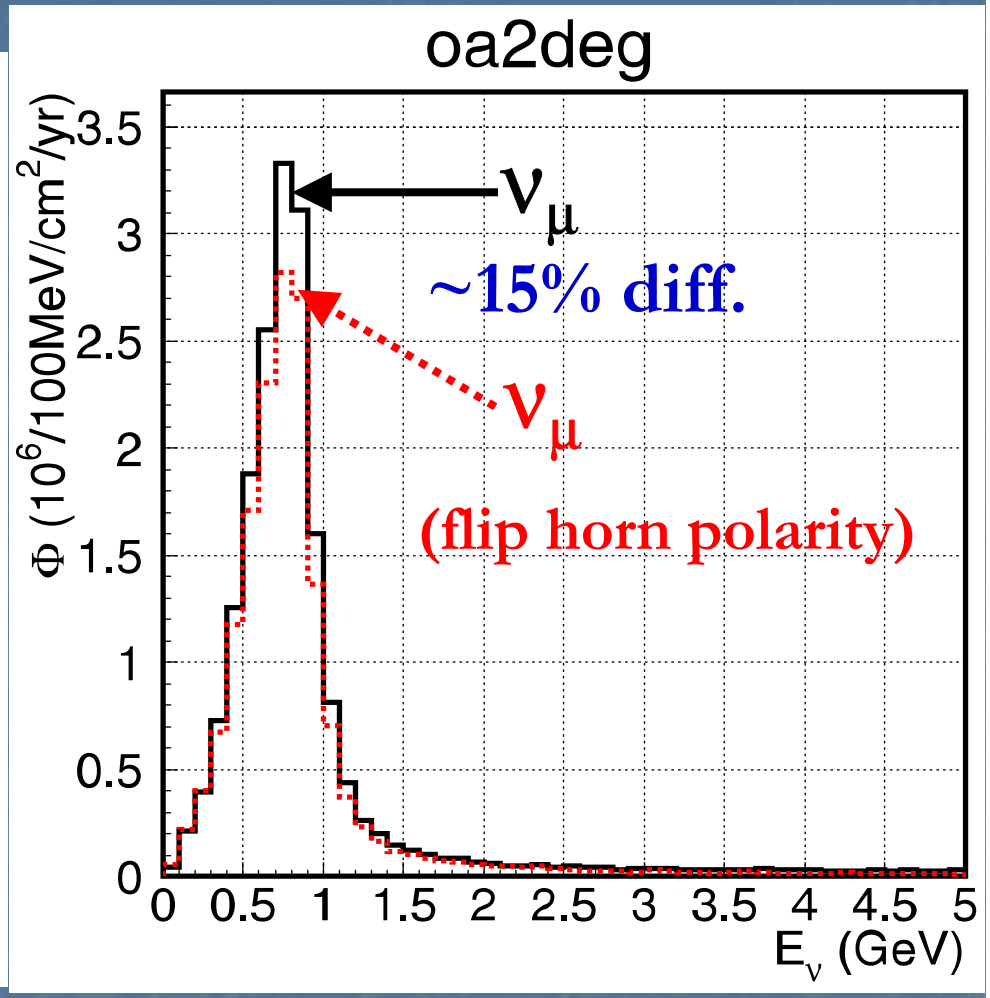
Target-SK distance=295km

Condition

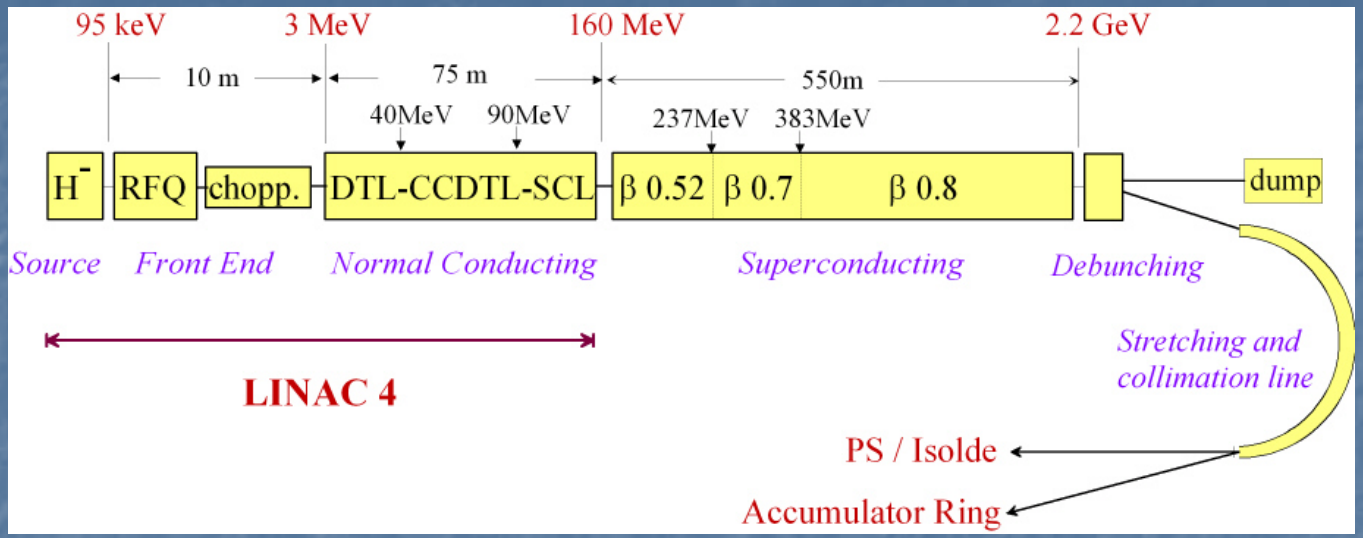
		Bessel Coodinate	Direction Angle
Target	E	36° 26'45.4976"	
	N	140° 36'27.7413"	
	H	-1.7m	
SK	E	36° 25'21.4935"	270.4764
	N	137° 18'48.0468"	1.2626
	H	321.216m	
HK	E	36° 21'08"	268.9618
	N	137° 18'49"	1.2463
	H	412.175m	

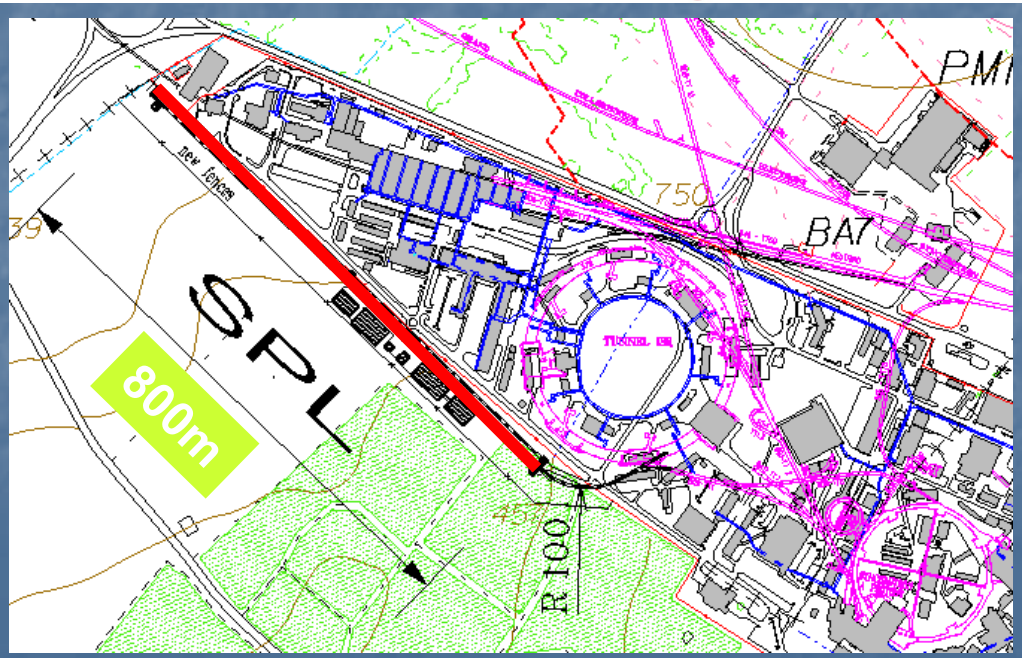
ν / ν̄ beam flux


OAB (2degree)
ν_μ
0.21%
μ-decay
ν_e
K-decay
Flux (/100MeV/cm^2/yr)
E_ν (GeV)


oa2deg
ν_μ
~15% diff.
ν_μ
(flip horn polarity)
Φ (10^6/100MeV/cm^2/yr)
E_ν (GeV)

Superconducting Proton Linac



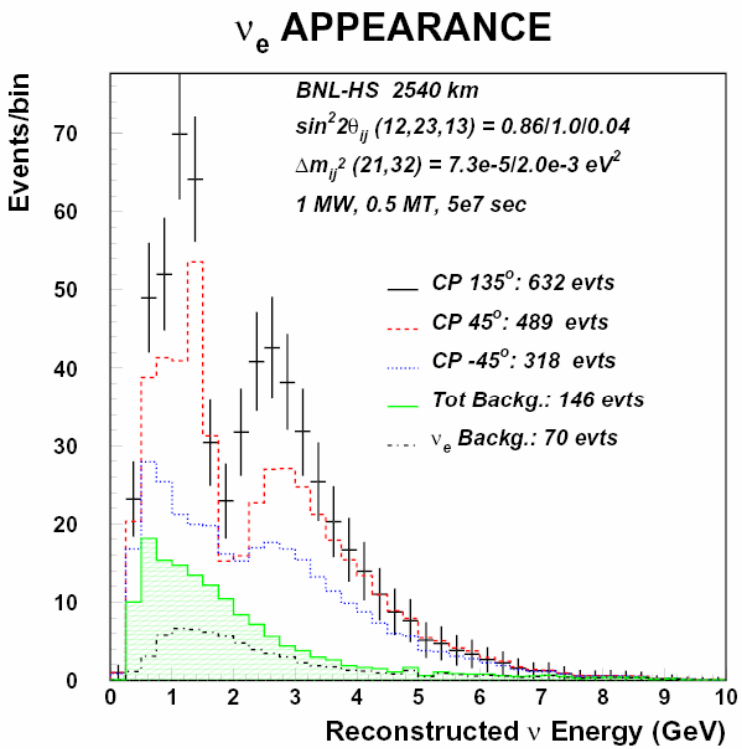


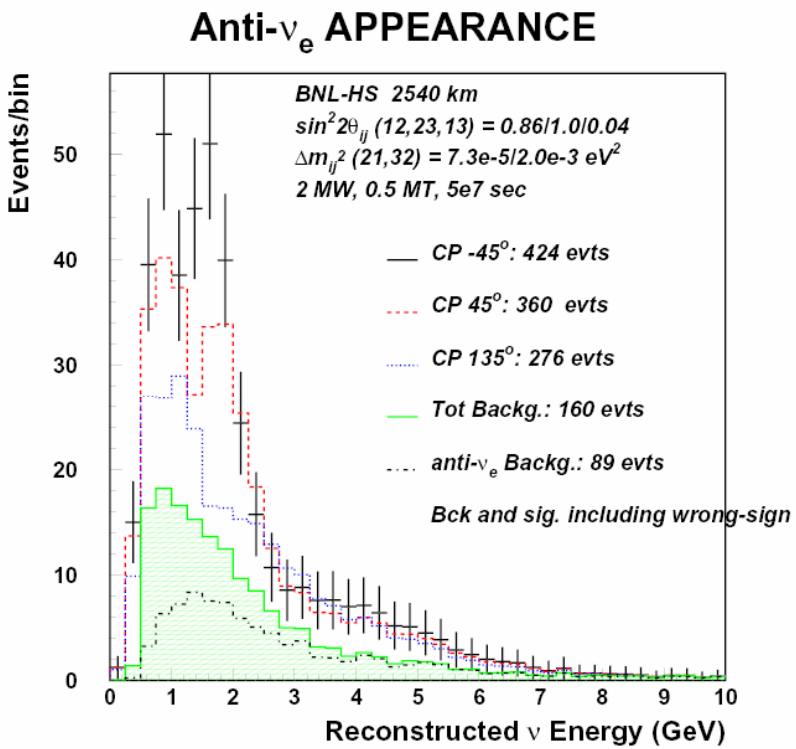
Brookhaven AGS Upgrade

Parameters

	Present	1 MW	2 MW
Total beam power [MW]	0.14	1.00	2.00
Injector Energy [GeV]	1.5	1.2	1.5
Beam energy [GeV]	24	28	28
Average current [μA]	6	36	72
Cycle time [s]	2	0.4	0.4
No. of protons per fill	0.7×10^{14}	0.9×10^{14}	1.8×10^{14}
Average circulating current [A]	4.2	5.0	10
No. of bunches at extraction	6	24	24
No. of protons per bunch	1×10^{13}	0.4×10^{13}	0.8×10^{13}
No. of protons per 10^7 sec.	3.5×10^{20}	23×10^{20}	46×10^{20}

Running for $\sin^2 2\theta_{13}$

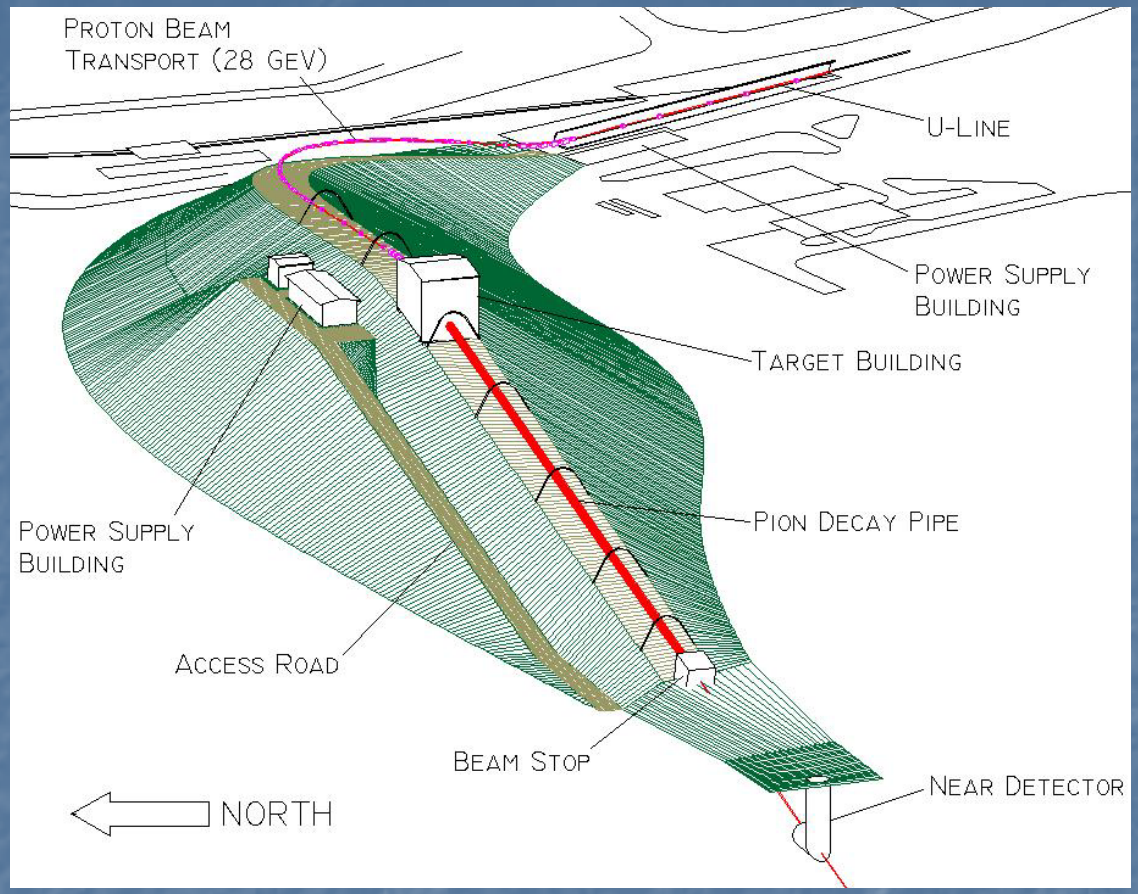




$\Delta m_{32}^2 = 0.002 eV^2$, $\sin^2 2\theta_{13} = 0.04$. Assume normal mass hierarchy. $m_3 > m_2 > m_1$ Matter effects included.

Diwan, Mar.2004

3-D Neutrino Super Beam Perspective



•The ν beamline is inclined 11.3º with respect to ground level to reach the Homestake mine

•Shielding is removed in figure to see the beamline.

•The hill is designed such that the target station, decay tunnel and beam dump are above the water table

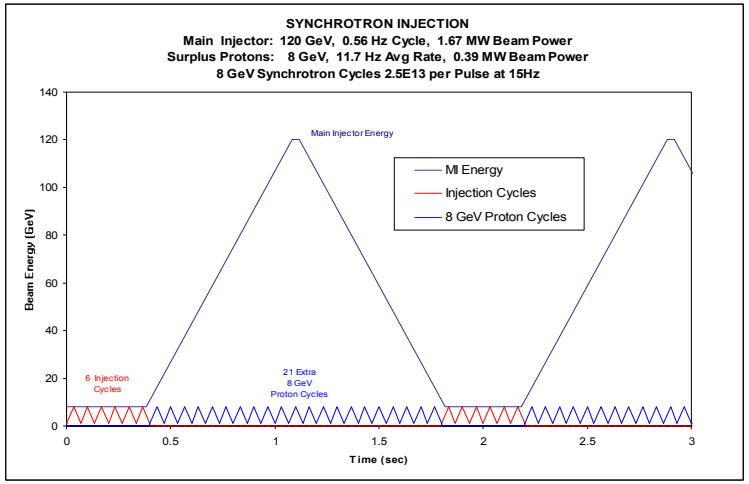
BROOKHAVEN NATIONAL LABORATORY

High Power Proton Drivers in US

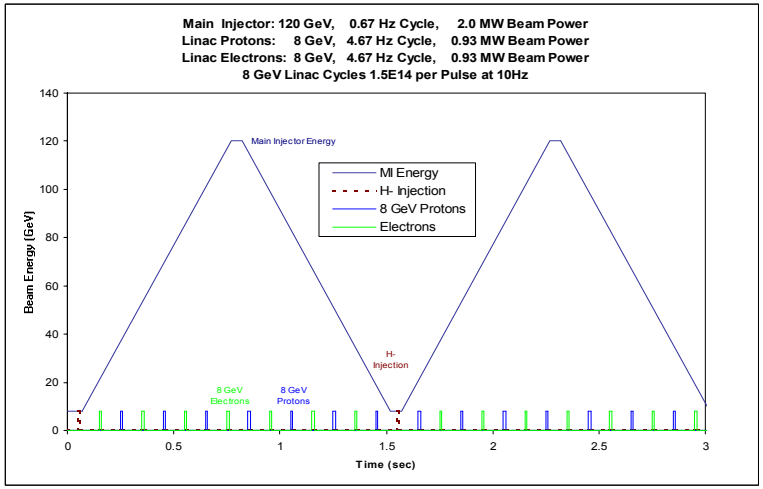
Performance Goals

		Fermilab Options			Brookhaven		
	Present	Synchrotron	Linac		Present	AGS Upgrade I	
Linac							
Kinetic Energy	400	600	**8000**		200	**1200**	MeV
Peak Current	40	50	25		40	30	mA
Pulse Length	90	90	1000		60	720	μsec
Protons/pulse	2.3E+13	2.8E+13	1.6E+14		1.5E+13	1.4E+14	
Repetition Rate	15	15	10		15	2.5	Hz
Average Beam Power	0.02	0.04	**2.00**		0.007	0.06	MW
Booster							
Kinetic Energy (Out)	8	8			1.5		GeV
Protons per Pulse	5.0E+12	2.5E+13			1.5E+13		
Repetition Rate	7.5	15			6.7		Hz
Protons/hour	1.4E+17	1.4E+18			3.6E+17		
Average Beam Power	0.05	**0.5**			0.02		MW
Main Injector				**AGS**			
Kinetic Energy (Out)	120	**120**	**120**		24	**28**	GeV
Protons per Pulse	3.0E+13	1.5E+14	1.6E+14		6.0E+13	9.0E+13	
Repetition Rate	0.54	0.65	0.67		0.33	2.50	Hz
Protons/hour	5.8E+16	3.5E+17	3.8E+17		7.2E+16	8.1E+17	
Average Beam Power	0.3	**1.9**	**2.0**		0.1	**1.0**	MW

Fermilab Proton Driver
Main Injector Cycle Times

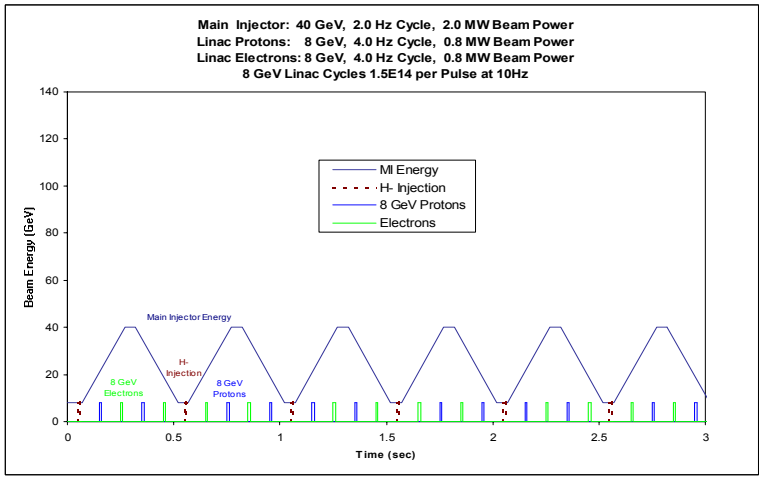


8 GeV Synchrotron



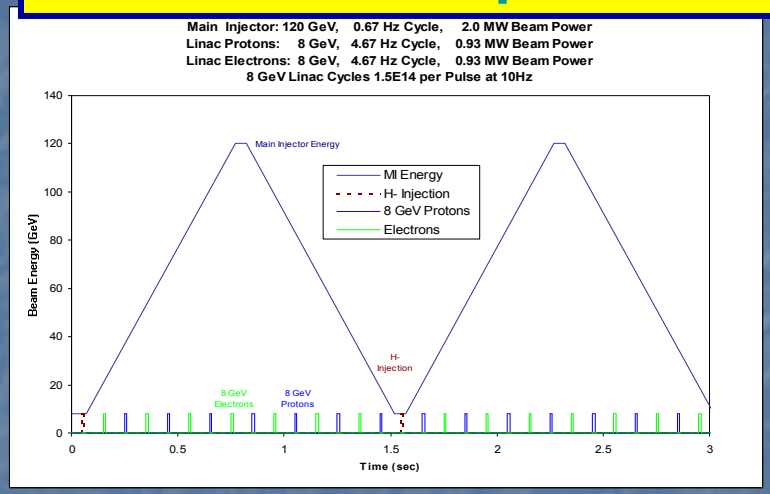
8 GeV Linac

Retains full beam power at lower energy (40 GeV)

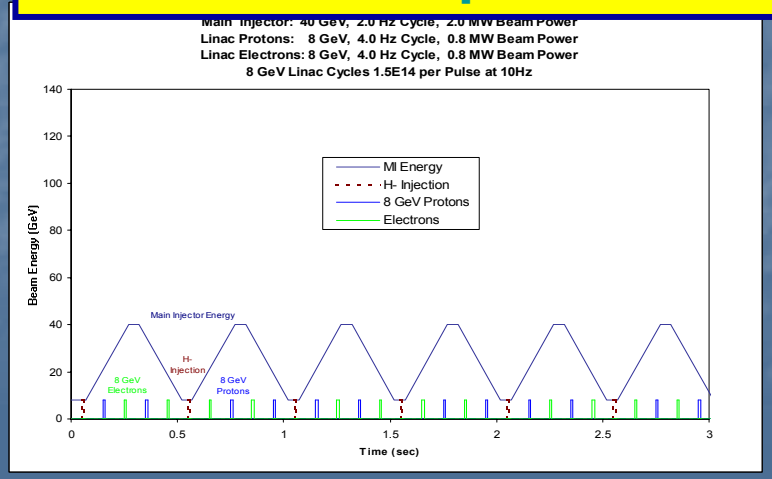


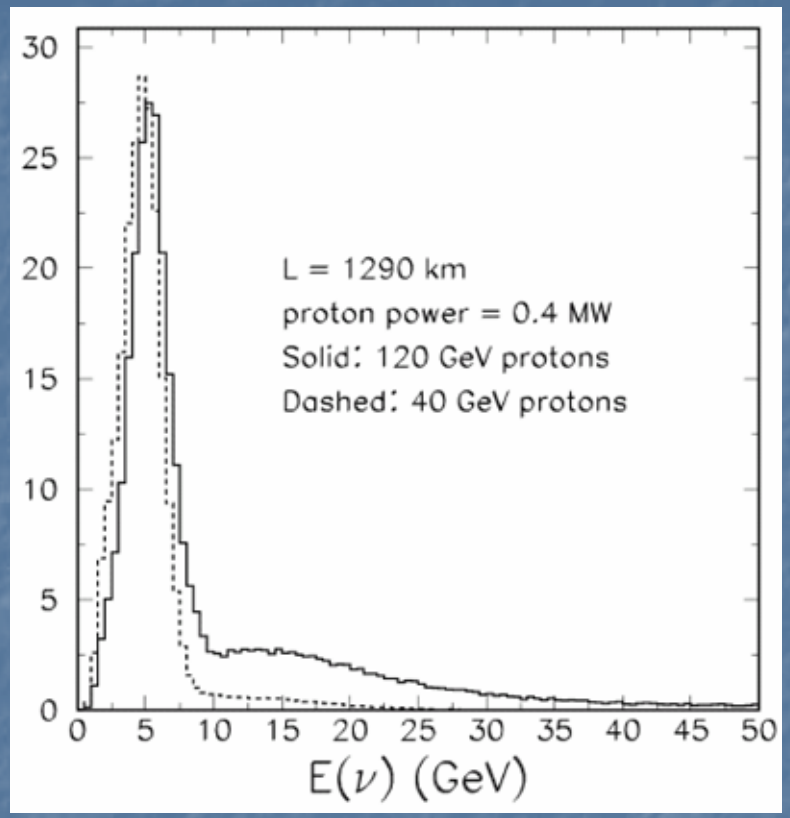
A possible advantage of Linac

LINAC + 120GeV operation case



LINAC + 40GeV operation case





Beam power indep from energy.
Almost same flux with reduced HE tail at 40GeV compared with 120GeV