Lomonosov 11
@ Moscow
Aug. 23

Long baseline (LBL) neutrino experiments

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Contents

Introduction

- Evidences of ν oscillation in atm ν & solar ν
  - Finite masses
  - Large mixings!
  - New era of "neutrino flavor physics!!"
- Still many mysteries in neutrino physics
  - Why so light?
  - Why so differently mix from quark sector?
  - How many (sterile) neutrinos?
  - Absolute mass?/ hierarchy?
  - Majorana? Dirac?
  - CPV?
  - Almost "unknown" compared w/ quarks
- Understanding properties of neutrino will provide clue toward physics beyond the standard model
  - GUT (Seesaw model,..)
  - Leptogenesis
  - Extra dimensions….
- Full exploration of whole structure of neutrino masses and mixing is a critical step

Neutrino mixing

If neutrino have finite mass, weak and mass eigenstates can differ

$$|\nu_l\rangle = \Sigma U_{li} |\nu_i\rangle$$

Weak　　Mass eigenstates

m_i: 3 masses, Δm_{ij}: 2 differences

Maki-**N**akagawa-**S**akata **Matrix**　$s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

3 mixing angles and 1 CPV phase

Unknown 2 parameters

$$= \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

$\sin^2 2\theta_{12} \sim 0.8$ (Solar)

$\sin^2 2\theta_{23} \sim 1$ (Atm ν)

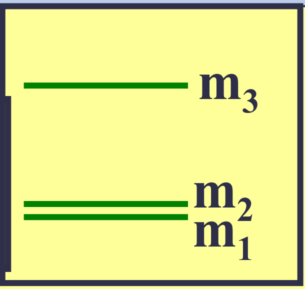
Reactor

Long baseline experiments

Neutrino oscillation

Oscillation probabilities

$$\Delta m_{12}^2 << \Delta m_{23}^2 \approx \Delta m_{13}^2 = \Delta M^2$$
$$\Delta m_{ij}^2 = m_j^2 - m_i^2$$



- θ_{23} :ν_μ disappearance

$$P_{\nu\mu \to \nu\mu} \approx 1 - \underbrace{\cos^4 \theta_{13}}_{\sim 1} \cdot \sin^2 2\theta_{23} \sin^2 \left(1.27 \Delta M^2 L / E_\nu\right)$$

- θ_{13} :ν_e appearance

$$P_{\nu\mu \to \nu e} \approx \underbrace{\sin^2 \theta_{23}}_{\sim 0.5} \cdot \sin^2 2\theta_{13} \sin^2 \left(1.27 \Delta M^2 L / E_\nu\right)$$

- δ: $\cancel{CP}$ in ν_e appearance

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \approx \frac{\Delta m_{12}^2}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta$$

1^{st} generation LBL experiments

-- Confirmation atm ν resutls –

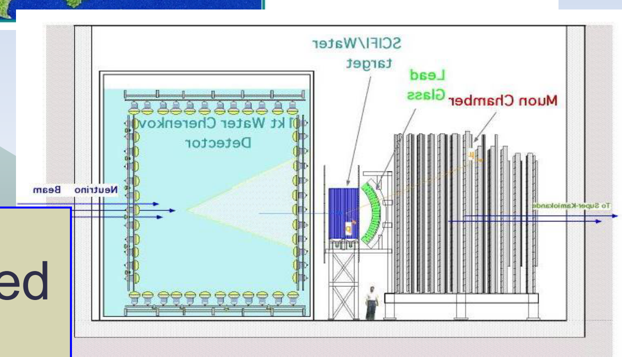
w/ well controlled systematics

- Known distance
- Known direction
- Known (measurable) flavor content, spectrum

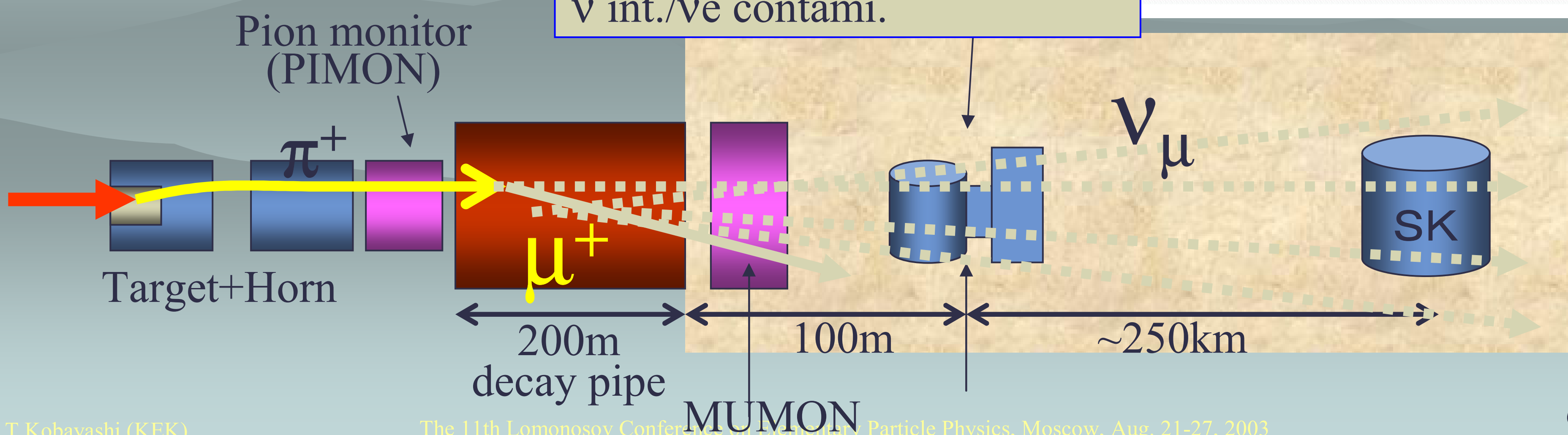
K2K experiment (since 1999)

First long baseline (250km) neutrino experiment.

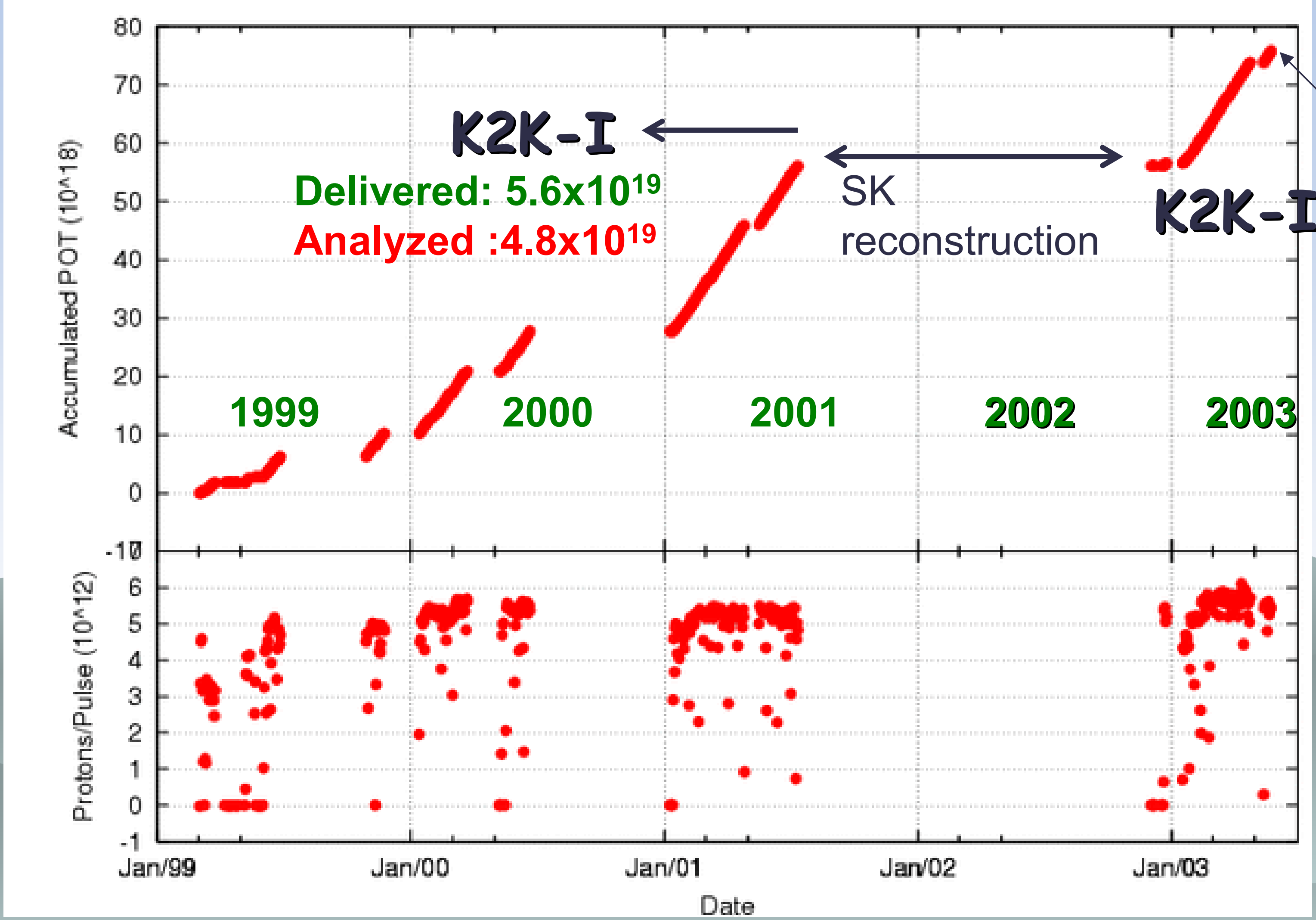
- 12GeV PS
- Pure νμ beam (99%) w/ <Eν>~1.3GeV
- 50kt Water Ч (Super-Kamiokande)
- νμ disappearance and νe appearance



Near detector(ND)
1kt Water Ч + Fine grained
Normalization/Spectrum
ν int./νe contami.



Delivered protons on target (POT)

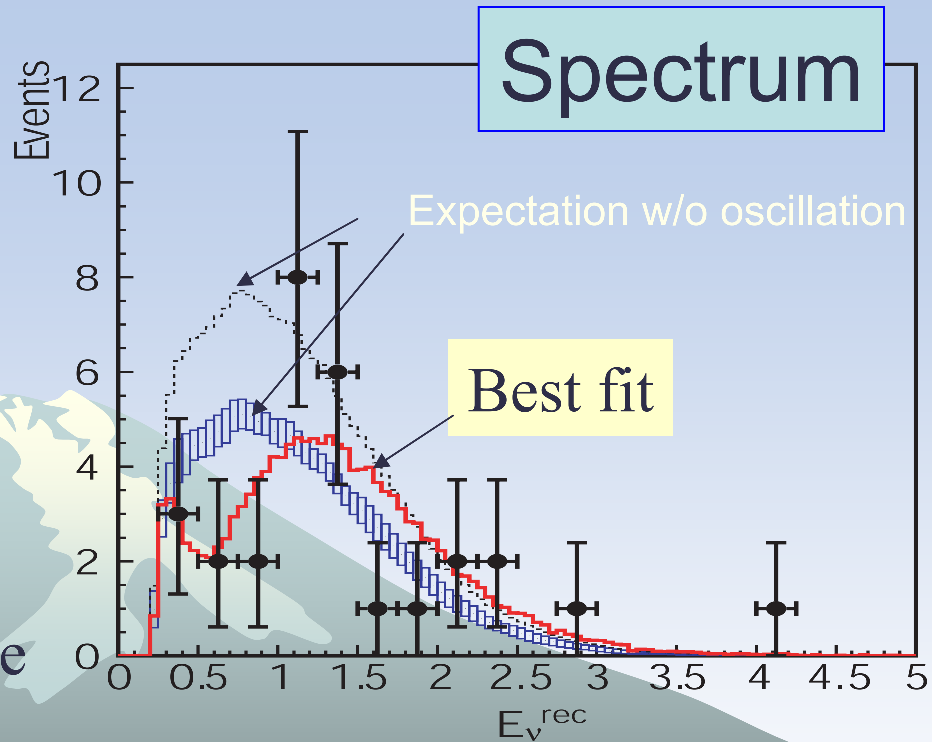


Plan to accumulate 10^{20} analyzed POT

PRL**90**(2003)041801

ν_μ disappearance

- Signature
  - Decrease in # of evts
  - Spectrum distortion
- Selection
  - For #evts: Fully contained in fiducial volume (FCFV)
  - For spect.:FCFV, 1-ring m-like (1Rμ)
- Results
  - # of evts
    - **Obs : 56 evts**
    - Exp'ed : $80.1^{+6.2}_{-5.4}$ (w/o osc)

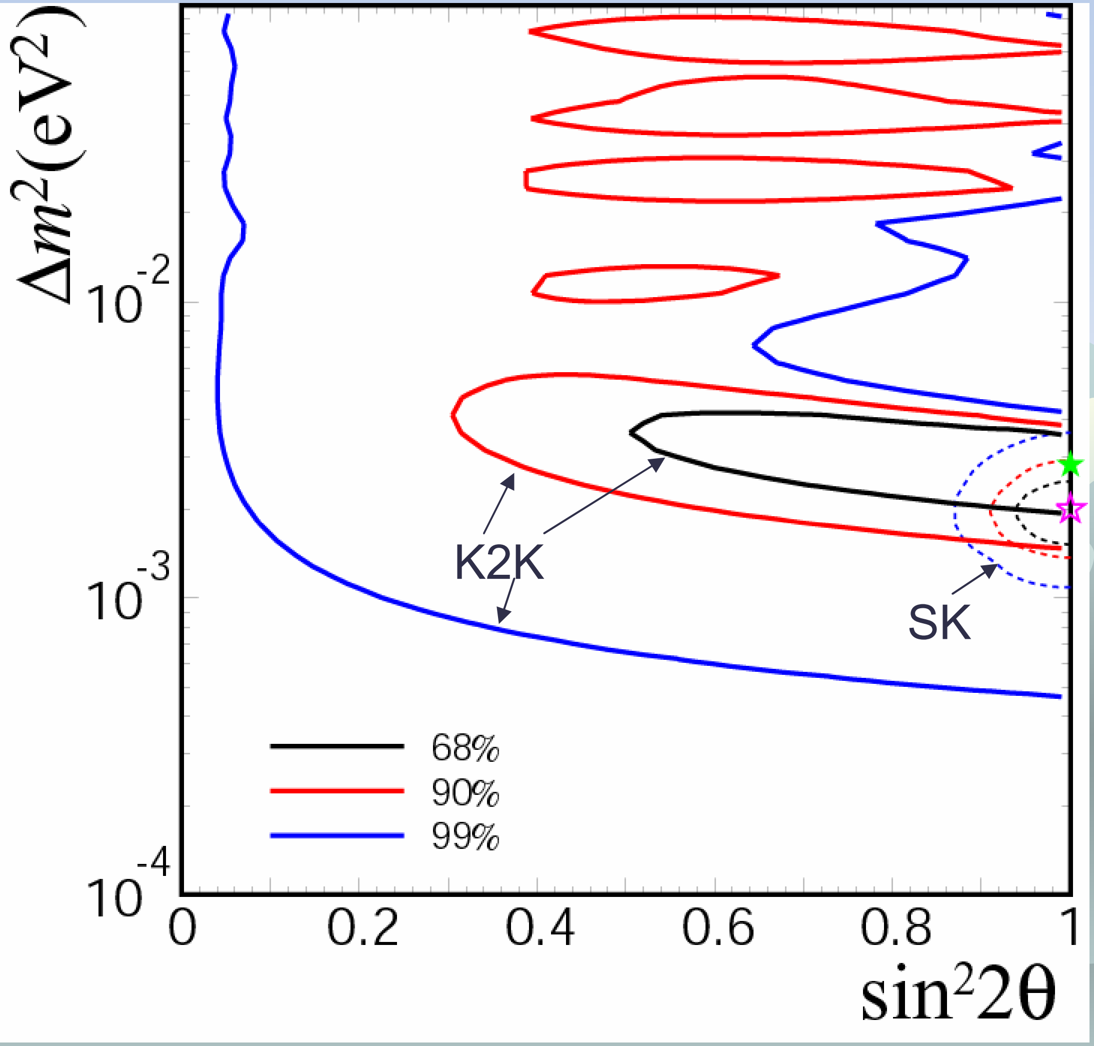


@Best fit $\sin^2 2\theta = 1$, $\Delta m^2 = 2.8\times10^{-3}$ eV^2

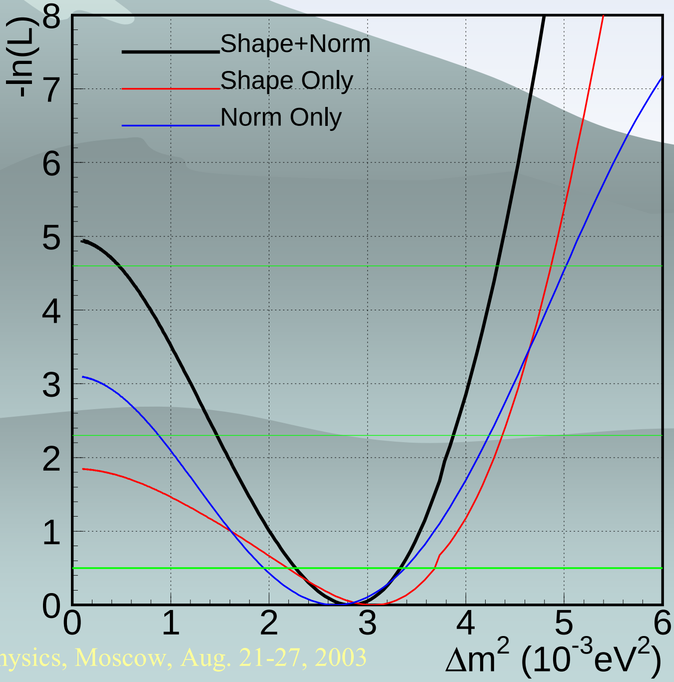
- Spectrum shape: KS test:79%
- # of events :54evts

Both Shape & N_{SK} agree with best fit expectation

Constraint on osc. parameters



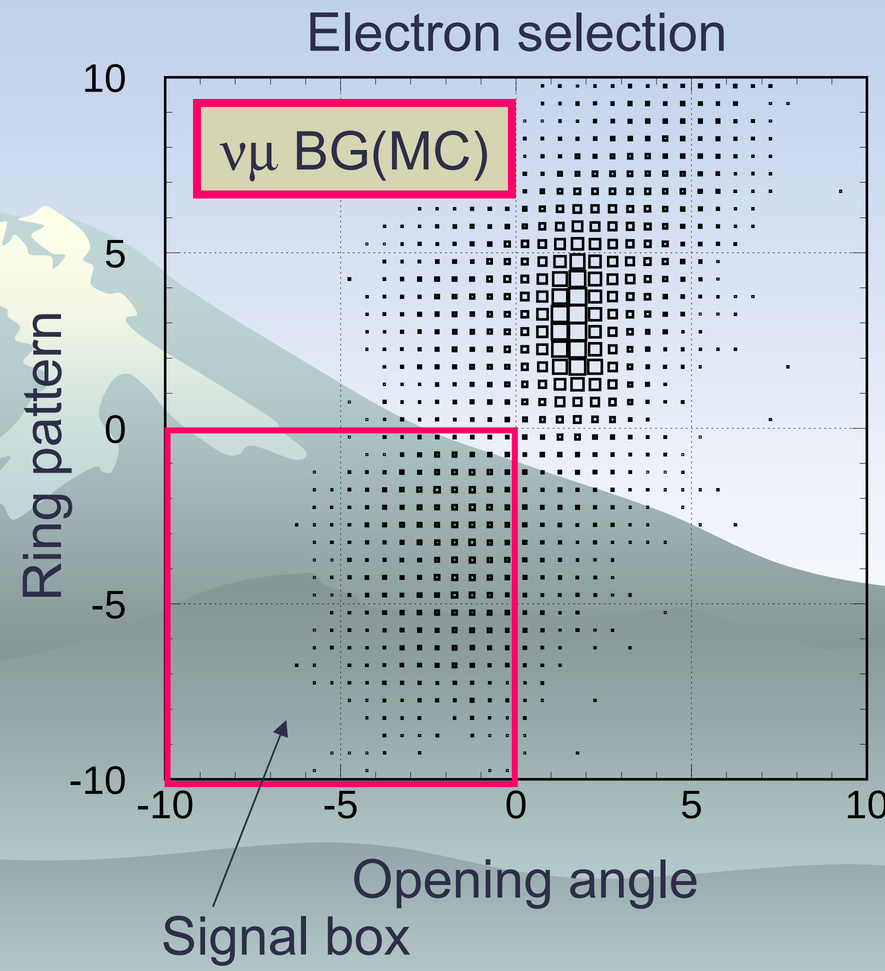
- $1.5\sim3.9\times10^{-3}\mathrm{eV}^2$ @ $\sin^2 2\theta=1$(90%CL)
- consistent w/ SK
- Null osc. prob. < 1%
- # of events & spectrum shape indicate same Δm^2 region



The first ν_e appearance search in K2K

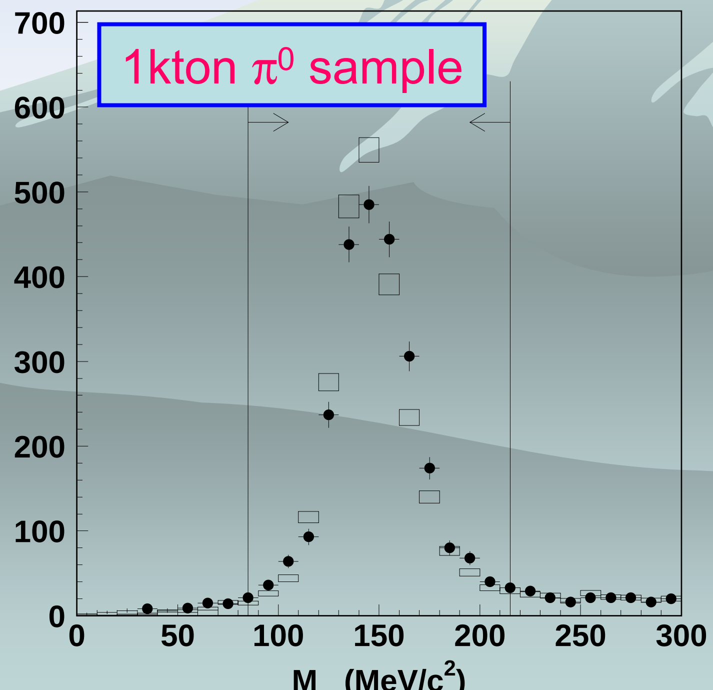
- Selection
  - Fully Contained in Fiducial Volume (FCFV)
  - Single electron-like ring (1R-e)
  - Visible Energy > 100MeV
  - No decay electrons associated
- Background
  - ν_μ NC π^0 w/ missing 1γ
  - Beam intrinsic ν_e (flux ν_e/ν_μ~1%)

- POT: 4.8×10^{19} (Jun.`99~Jul.`01)
- **Observed : 1 evt**
- **Backgrounds : 2.4±0.6 evts**
  - ν_μ 2.0 ±0.6 evts. (NC87%)
  - ν_e 0.35±0.11 evts
- **Exp'ed sig : 16 evts**
  - @ full $\nu_\mu \rightarrow \nu_e$ mixing, $\Delta m^2=2.8\times10^{-3}eV^2$
  - 55% eff.



Background estimation

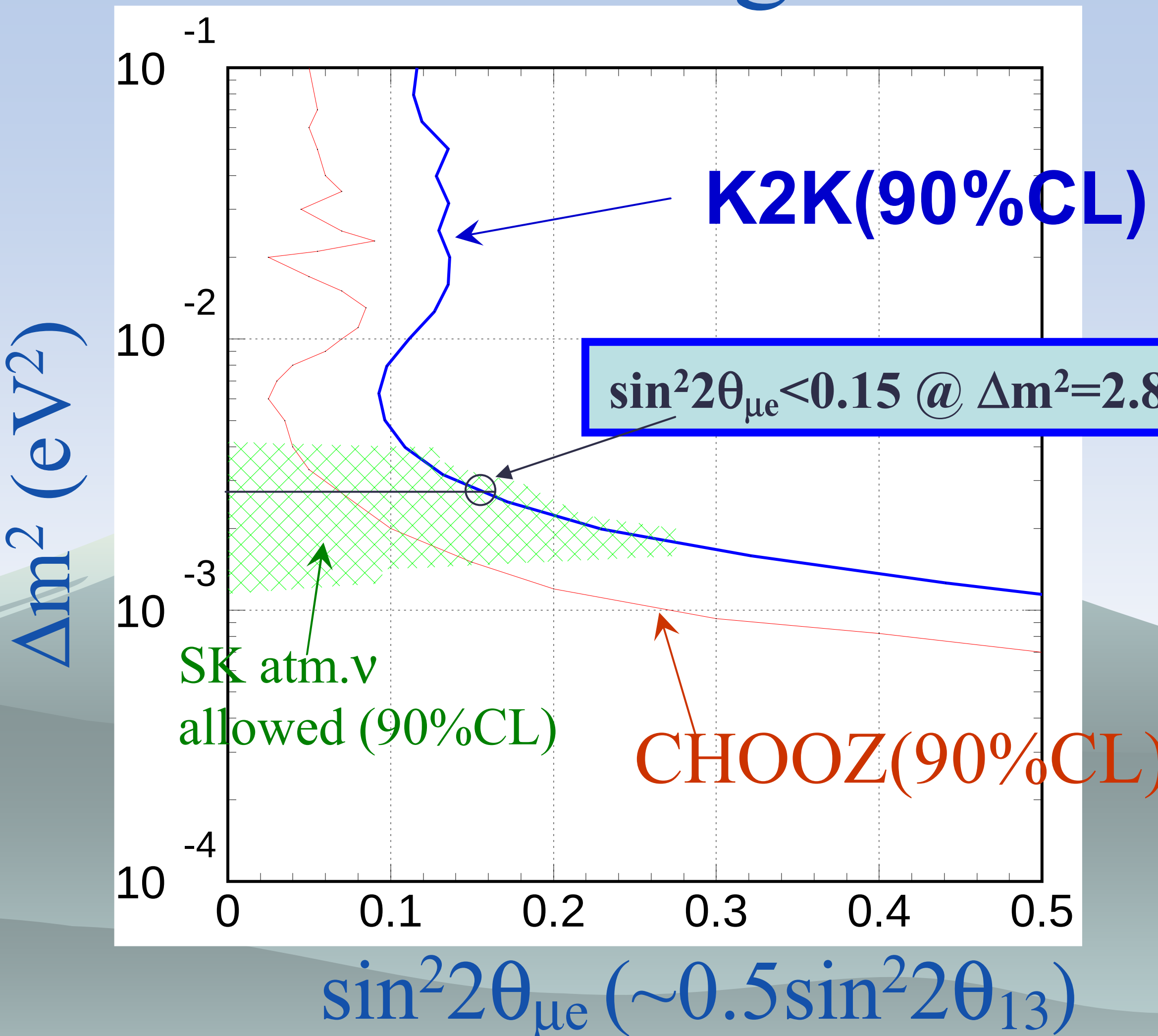
- $N_{BG}^{\nu e}$ **= 0.35±0.11 evts**
  - ν_e/ν_μ from beam MC
  - Beam MC confirmed by ND ν_e meas.
- $N_{BG}^{\nu\mu}$ **= 2.0±0.6 evts** (w/o oscillations)
  - Dominated by NCπ^0 (87%)
  - Constraint on NC cross-section
    - 1kt π^0/(1-ring μ) ratio measurement
      π^0~85%NC, 1R-μ:~100%CC → NC/CC



Major sources of syst. err. in ν_μ BG

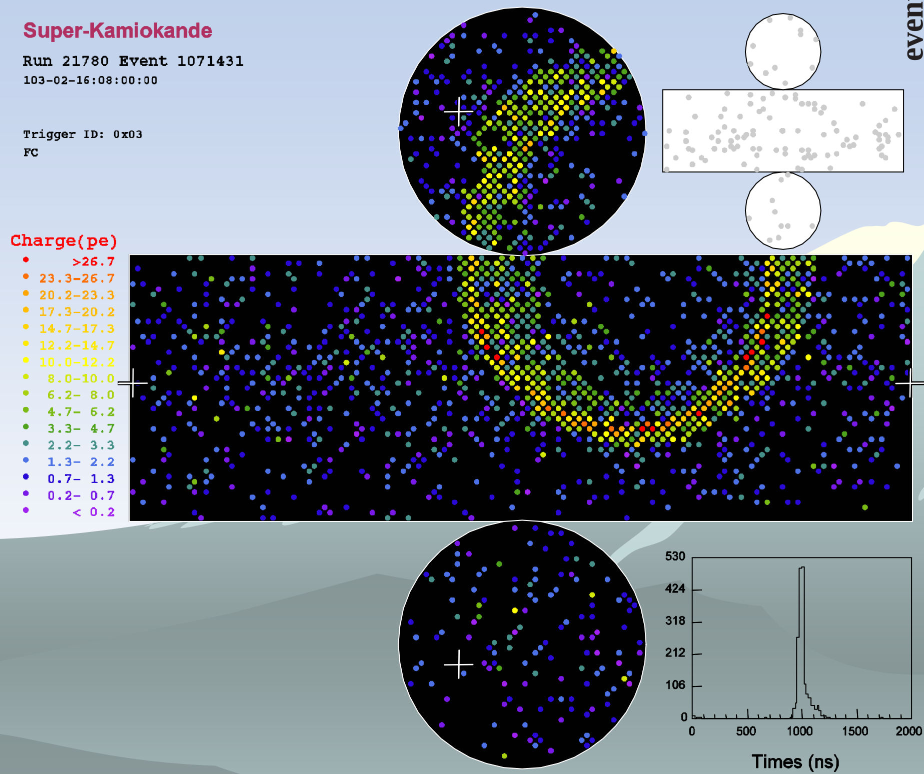
KT (~fid. vol.)	±4.4%
SK (~fid. vol.)	±3.0%
Ring count	+15% −13%
PID	+10% −11%
Far/Near	(±5.8%)
Spectrum	(+8.7%) (−9.4%)
NC/CC	(+22%) (−23%)

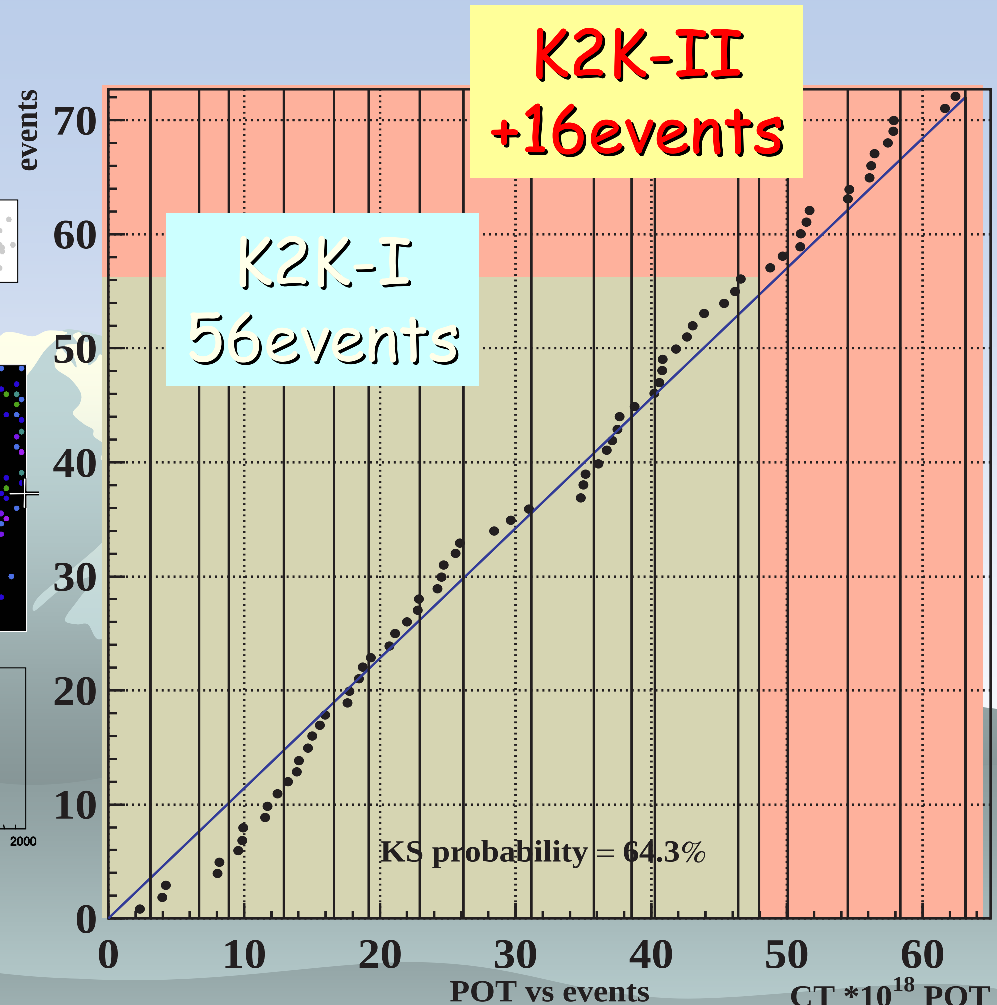
Excluded region



The first accelerator-based ν_e (not anti-ν_e) appearance search around $10^{-(3\sim2)}$eV^2 region!!

K2K resumed.

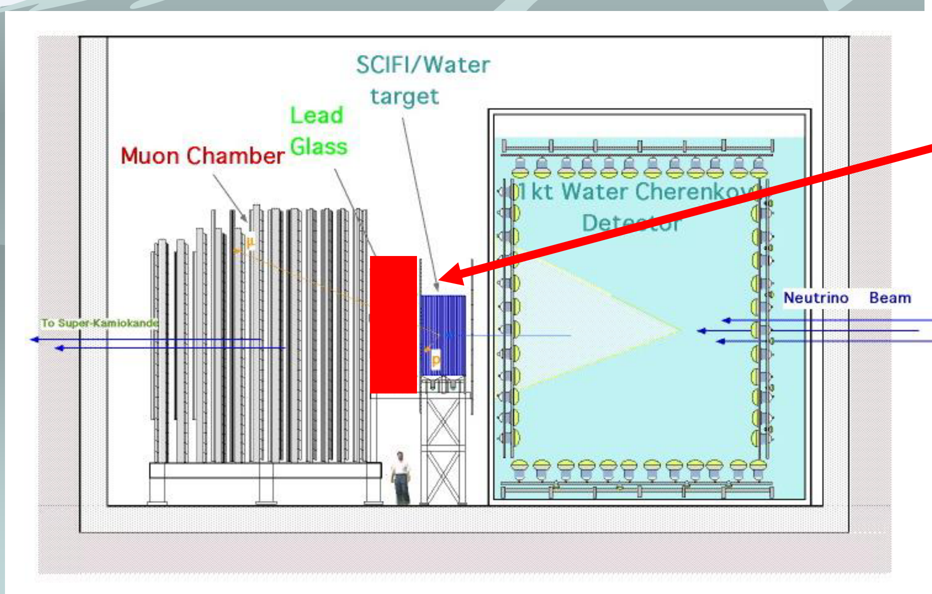


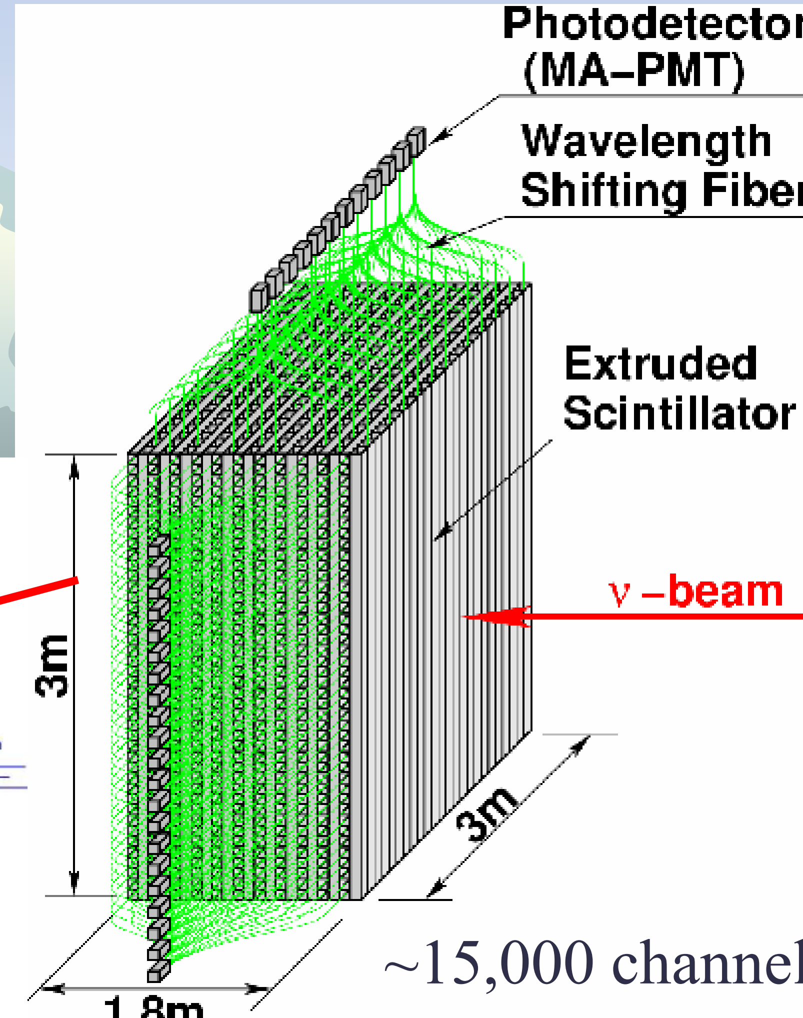


Event rate ([Observed # of events] / [POT]) for K2K-II consistent with K2K-I

K2K Upgrade (SciBar detector)

- L=250km, $\Delta m^2 = 3\times10^{-3}$ Eν ~ 0.6GeV
- **Study LE ν int. to maximize K2K sensitivity**
  - **QE, single/multi π production,..**
- **Full Active (solid) Scintillator Tracker**
- **+CHORUS EMcal**
- **All scintillator installed**
- Fibers/PMTs/Electronics installation going
- Commissioning in September



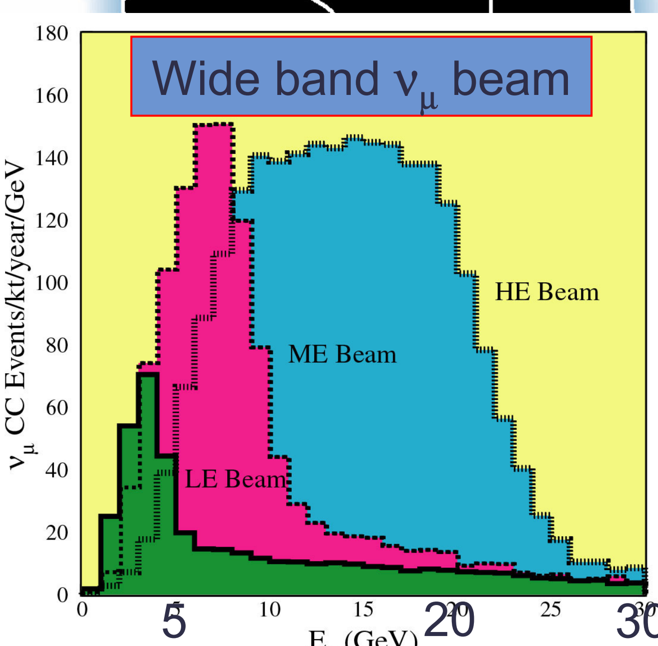


~15,000 channels

All scintillator installation finished

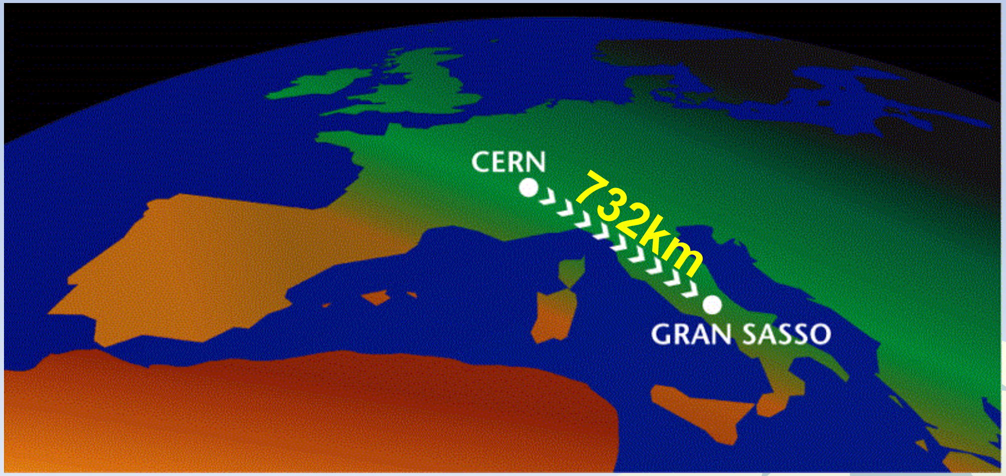
	6/22	6/23	6/30	7/7	7/14	7/21	7/28	8/4	8/11	8/18	8/25	9/1	9/8	9/15
	beam													
	end													
e-calorimeter														
Layer														
Fiber, PMT, FEB														
comissioning														

MINOS

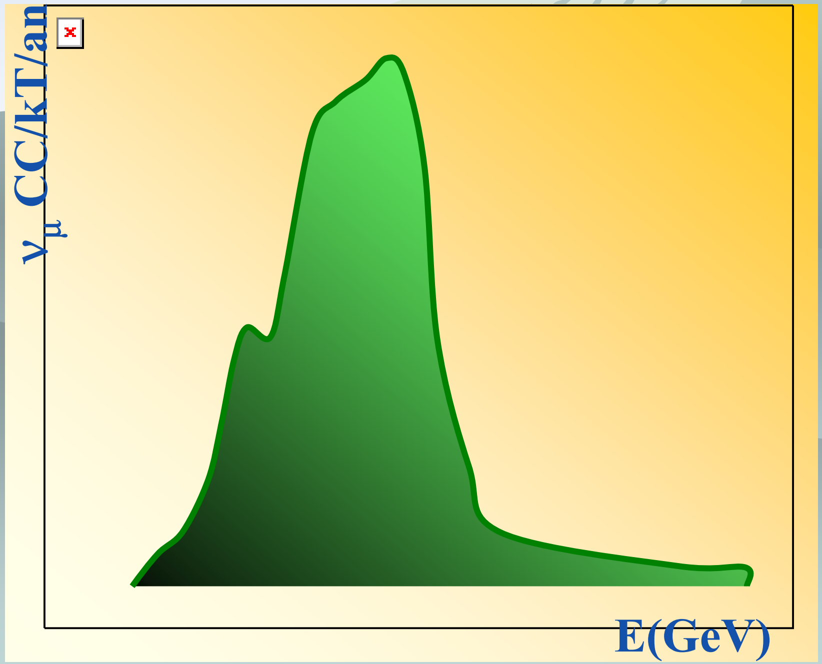


- FNAL 120GeV Main Injector (0.4MW) → Soudan mine (735km)
- Horn-focused wide band ν_μ beam
  - ν_μ CC int./MINOS/yr ~ 2,500 (LE beam)
- (magnetized)Iron-scintillator sampling calorimeter
  - 5,400tons @ far, 980tons @ near
  - 55%/√E for hadrons
  - 23%/√E for electrons
- ν_μ disappearance
  - Oscillatory behavior
  - Precise determination of Δm_{23}^2, θ_{23}
- Start from 2005
  - **Far detector completed July 10, 2003**
  - First proton on target Dec., 2004

CERN neutrino to Gran Sasso (CNGS)

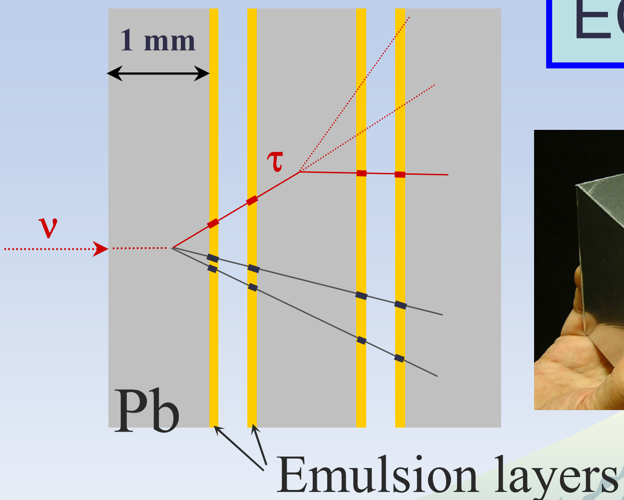


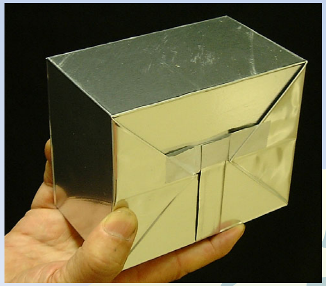
- CERN 400GeV SPS → Gran Sasso (732km)
- **ν_τ appearance** (+ ν_e appearance)
- 6.8×10^{19}POT/yr (x1.5 granted)
- Wide band ν_μ beam
  - $<E_\nu>$~17GeV
- ~5500ν_μ event/kt/yr
- **First beam to GS May 2006**
  - Underground civil const. finished Jun.20,2003
  - Beam dump installation going
- Two experiments
  - OPERA
  - ICARUS



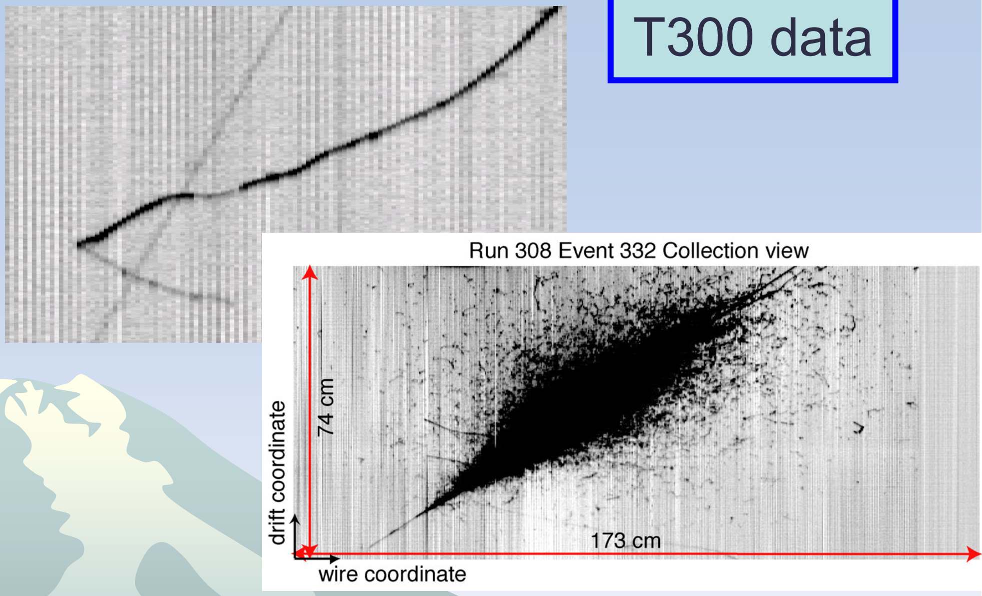
Detectors for CNGS

ECC





T300 data



OPERA

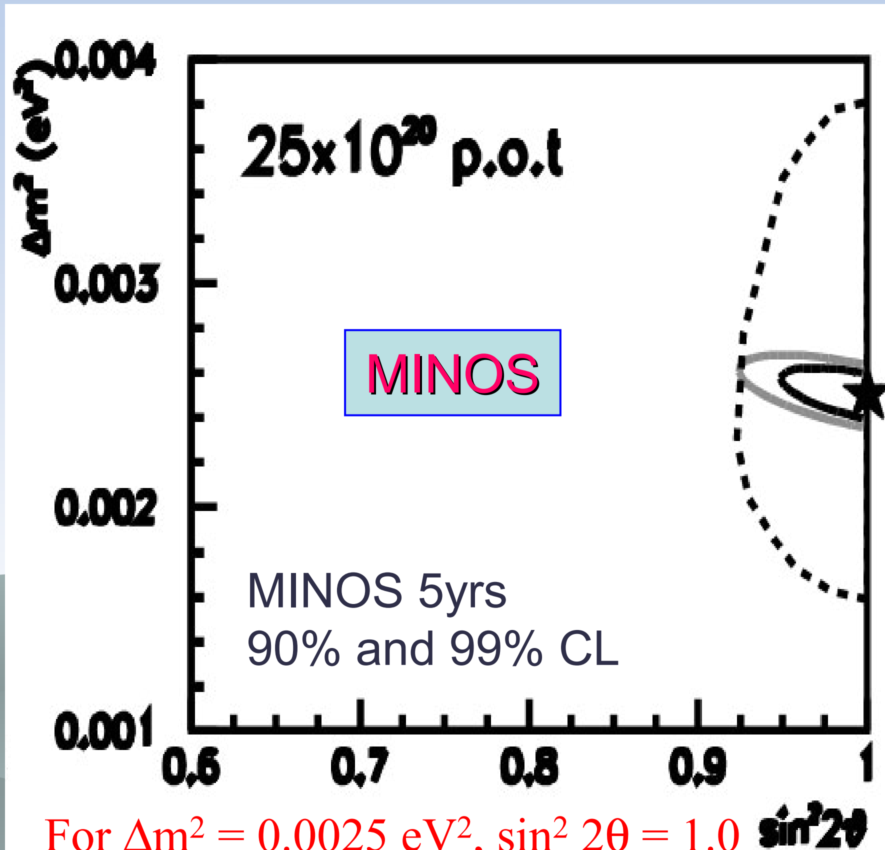
- **τ identification by decay topology (kink)**
- ECC (Emulsion Cloud Chamber)
  - Proven by DONUT experiment
  - **1.7kton** of ECC
  - 206,336 bricks
- Spectrometer (electronic tracker + 1.6T dipole)

ICARUS

- **τ identification by kinematic var. dist.**
- **3kton** Liq Ar TPC
- Constructed & proved performances of 300ton module at Pavia
- Installation of T600 module to Gran Sasso recommended
- Construction of 3kton by the CNGS beam (2006)

Expected sensitivites

ν_μ disappearance



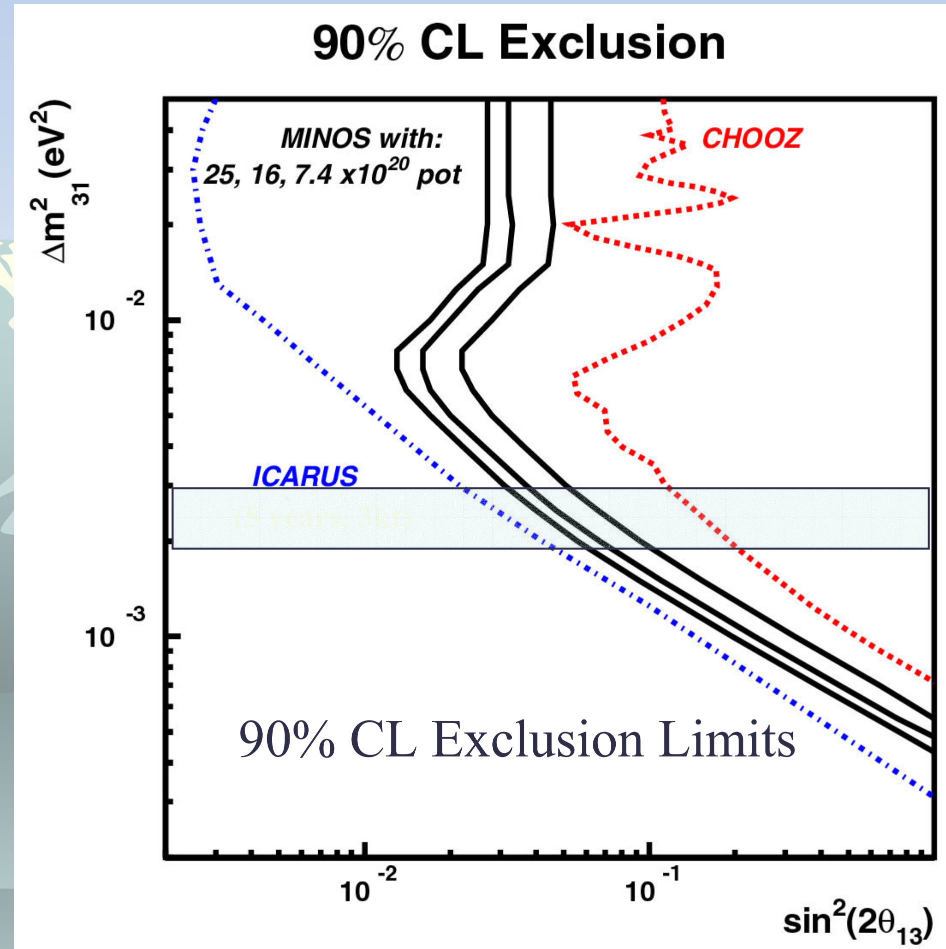
For $\Delta m^2 = 0.0025$ eV^2, $\sin^2 2\theta = 1.0$

$\delta(\Delta m^2) \sim 2\times10^{-4}$eV^2

$\delta(\sin^2 2\theta) \sim 5\%$

read from above plot

ν_e appearance



Expected # of ν_τ evts in 5yrs

• full mixing

OPERA

Δm^2 (x 10^{-3}eV^2)	signal 1.8	signal 2.5	signal 4.0	Back
Final Design	9.0	17.2	43.8	1.06*
With possible improvements**	10.3	19.8	50.4	0.67

* : 40% from charm
**: Changeable Sheet (+15% eff.), dE/dx (charm reduction by 40%)

ICARUS (T3000)

1.5 kton fiducial

τ decay mode	Signal $\Delta m^2 = 1.6 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 3.0 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 4.0 \times 10^{-3}$ eV^2	BG
$\tau \to e$	3.7	9	13	23	0.7
$\tau \to \rho$ DIS	0.6	1.5	2.2	3.9	< 0.1
$\tau \to \rho$ QE	0.6	1.4	2.0	3.6	< 0.1
Total	**4.9**	**11.9**	**17.2**	**30.5**	**0.7**

Goals of next generation LBL experiments

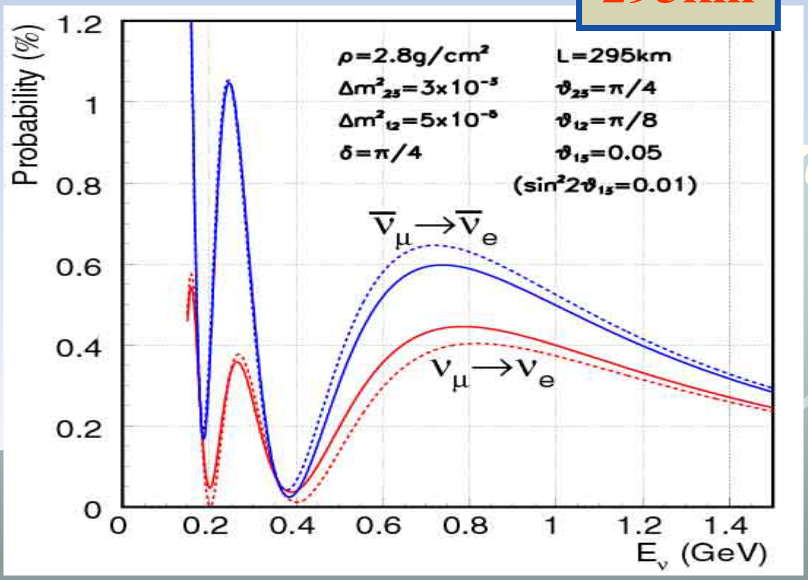
- Establish 3 flavor framework (or find something new)
  - Discovery of ν_e appearance (θ_{13}>0?)
    - At the same Δm^2 as ν_μ disapp. →Firm evidence of 3gen. mix.
    - Open possibility to search for CPV
  - Precision measurements of ocs. params.
    - $\Delta m_{23},\theta_{23}/\Delta m_{13},\theta_{13}$
    - Test exotic models (decay, extra dimensions,….)
- Sign of Δm^2
- **Search for CPV in lepton sector**
  - Give hint on Matter/Anti-matter asymmetry in the universe

CPV vs matter effect

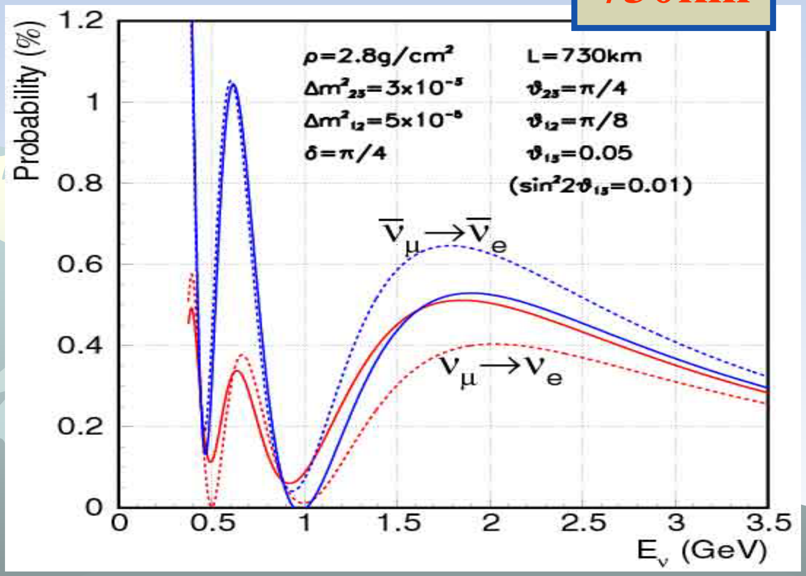
$\nu_\mu \rightarrow \nu_e$ osc. probability w/ CPV/matter

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

295km



730km



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

J-PARC-Kamioka project

Budget request submitted
4 year plan

(hep-ex/0106019)
http://neutrino.kek.jp/jhfnu

Kamioka

~1GeV ν beam

295km

JAERI (Tokaimura)

Super-K: 22.5 kt

Hyper-K: 1000 kt

0.75MW 50 GeV PS

4MW 50 GeV PS

~3000νμCC int/yr@SK in Phase-I

(conventional ν beam)

Phase-I (0.75MW + Super-Kamiokande) 2007(8)~

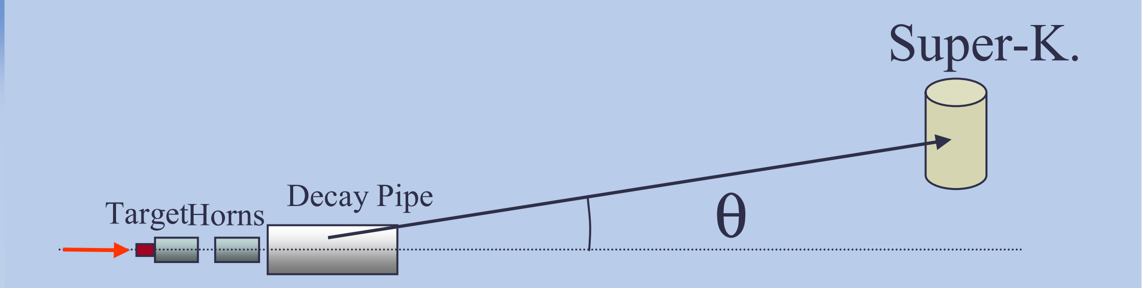
Phase-II (4MW+Hyper-K) ~ Phase-I × 200 201x?~

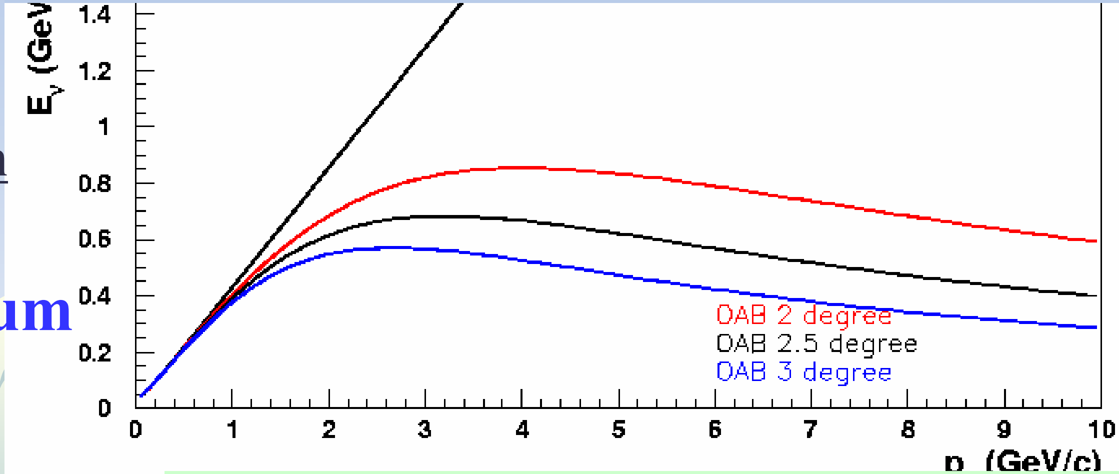
Off Axis Beam

(ref.: BNL-E889 Proposal)

- Quasi Monochromatic Beam
- x 2~3 intense than NBB

Tuned at oscillation maximum





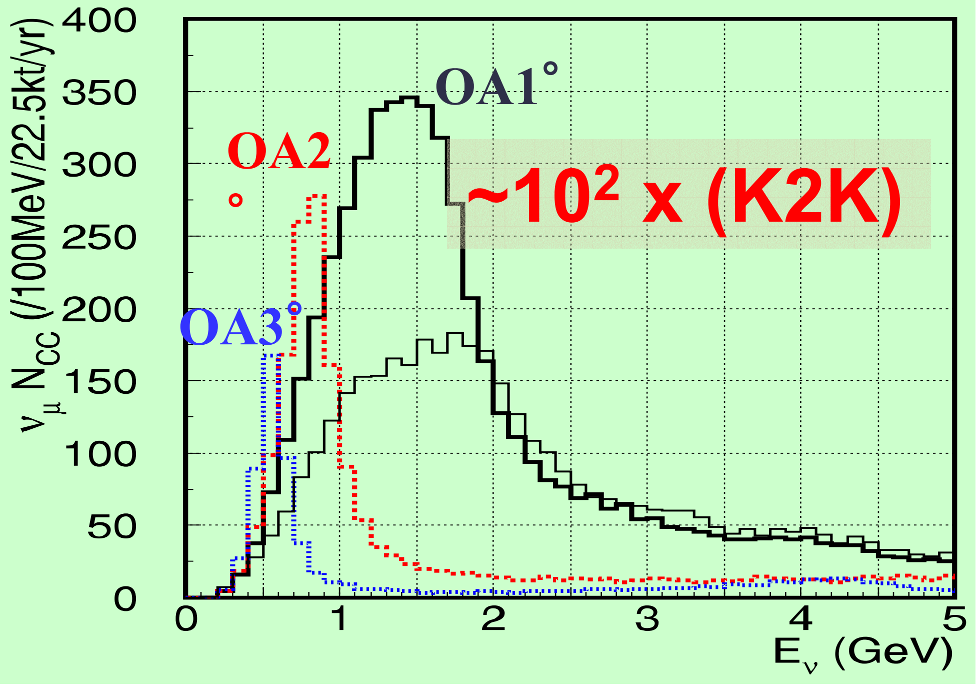
Statistics at SK

(OAB 2 deg,1 yr,22.5 kt)

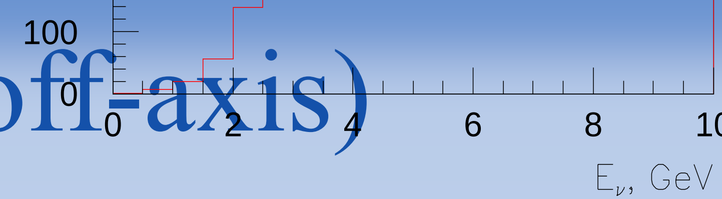
~ 4500 ν_μ tot

~ 3000 ν_μ CC

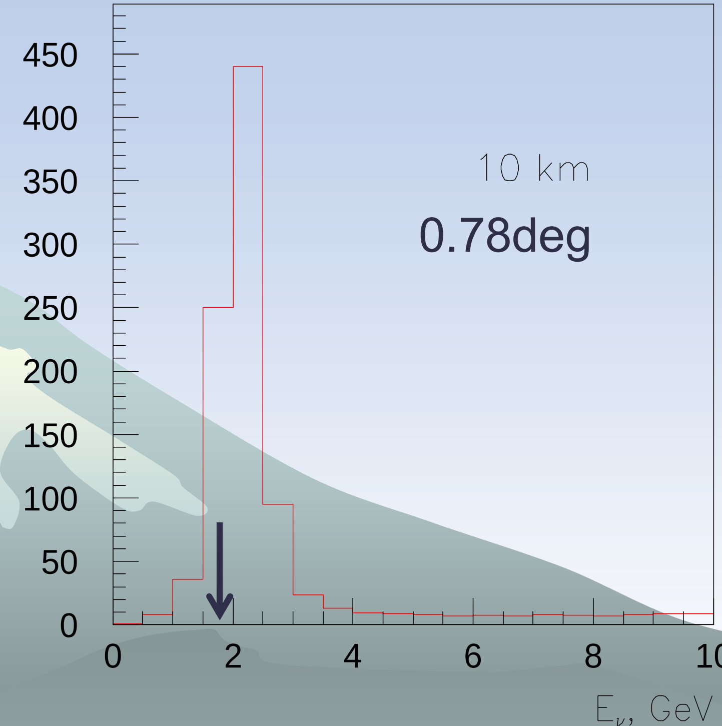
ν_e ~0.2% at ν_μ peak

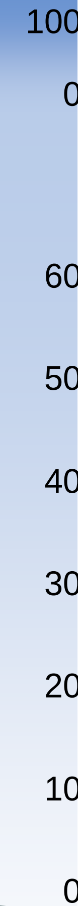


NuMI-OA (off-axis)



- Goal:
  - ν_e appearance,
  - precision measurements
  - CPV
- Use same beam line w/ MINOS
  - Can run w/ MINOS at the same time
- Several possible site 700~950km
- Several detector options
  - Low Z, fine grained
  - >50kton, 400k channels
  - Solid/liquid scintillator, glass RPSs, (Liq.Ar TPC)
- Staging
  - phaseI :50kt, 4×10^{20}POT/yr, 2008~
  - phaseII: 25 x (kt.pot in phaseI), 2014~, ν & anti-ν
- Complementary w/ J-PARC ν
  - Different L, Eν → diff. matter eff.



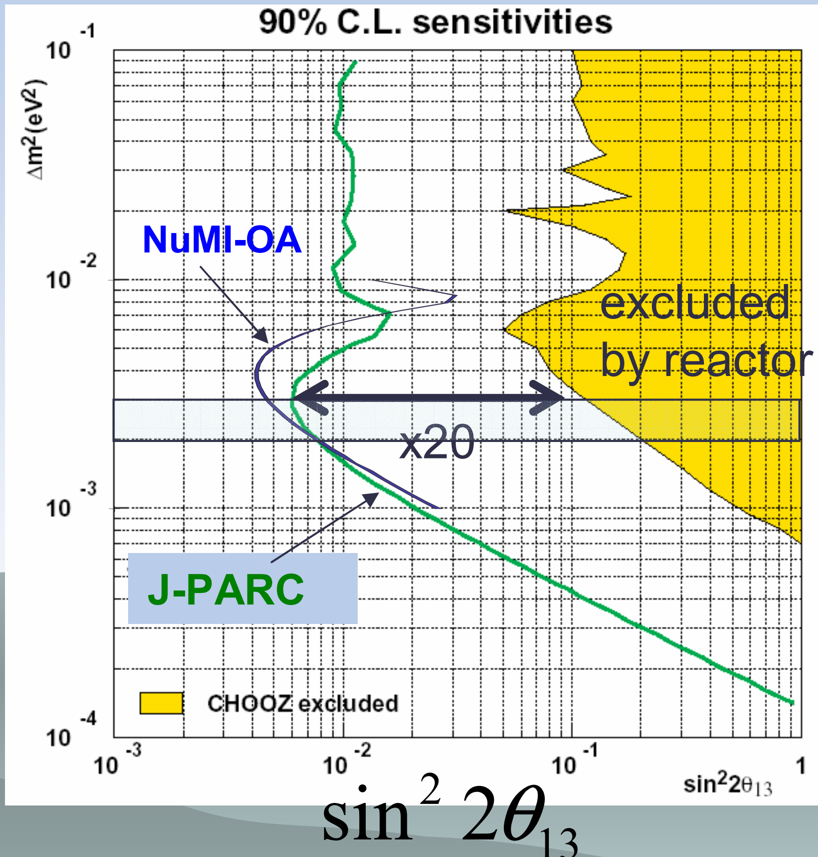


Osc. max. @ 730km
1.8GeV ($\Delta m^2=3\times10^{-3}$eV^2)

A. Para, M. Szleper, hep-ex/0110032

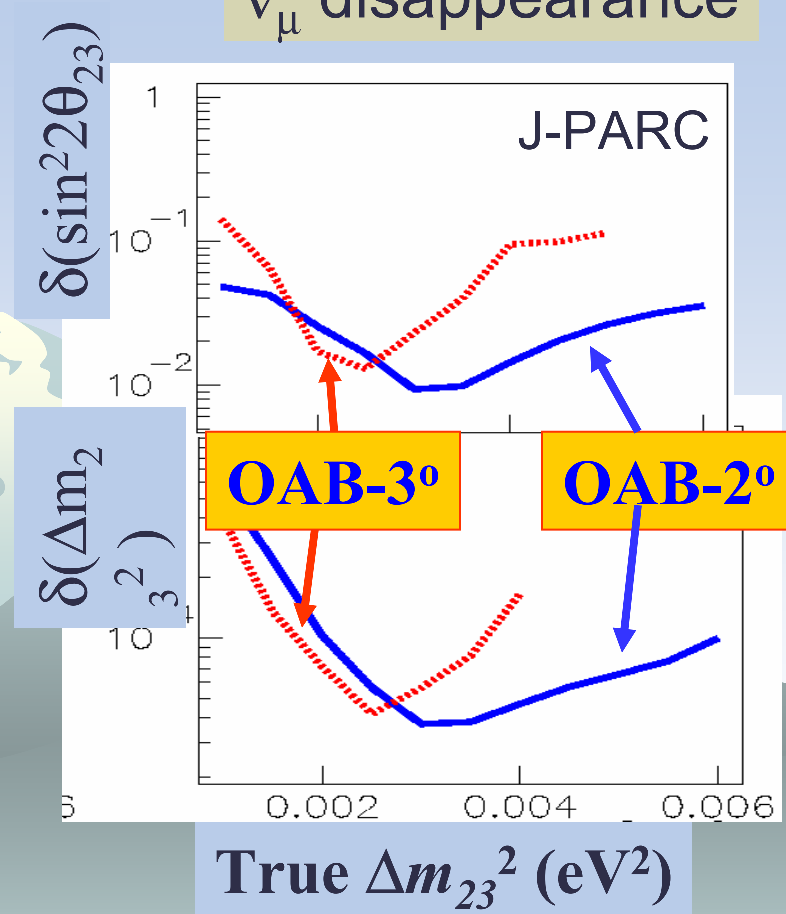
Sensitivities

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

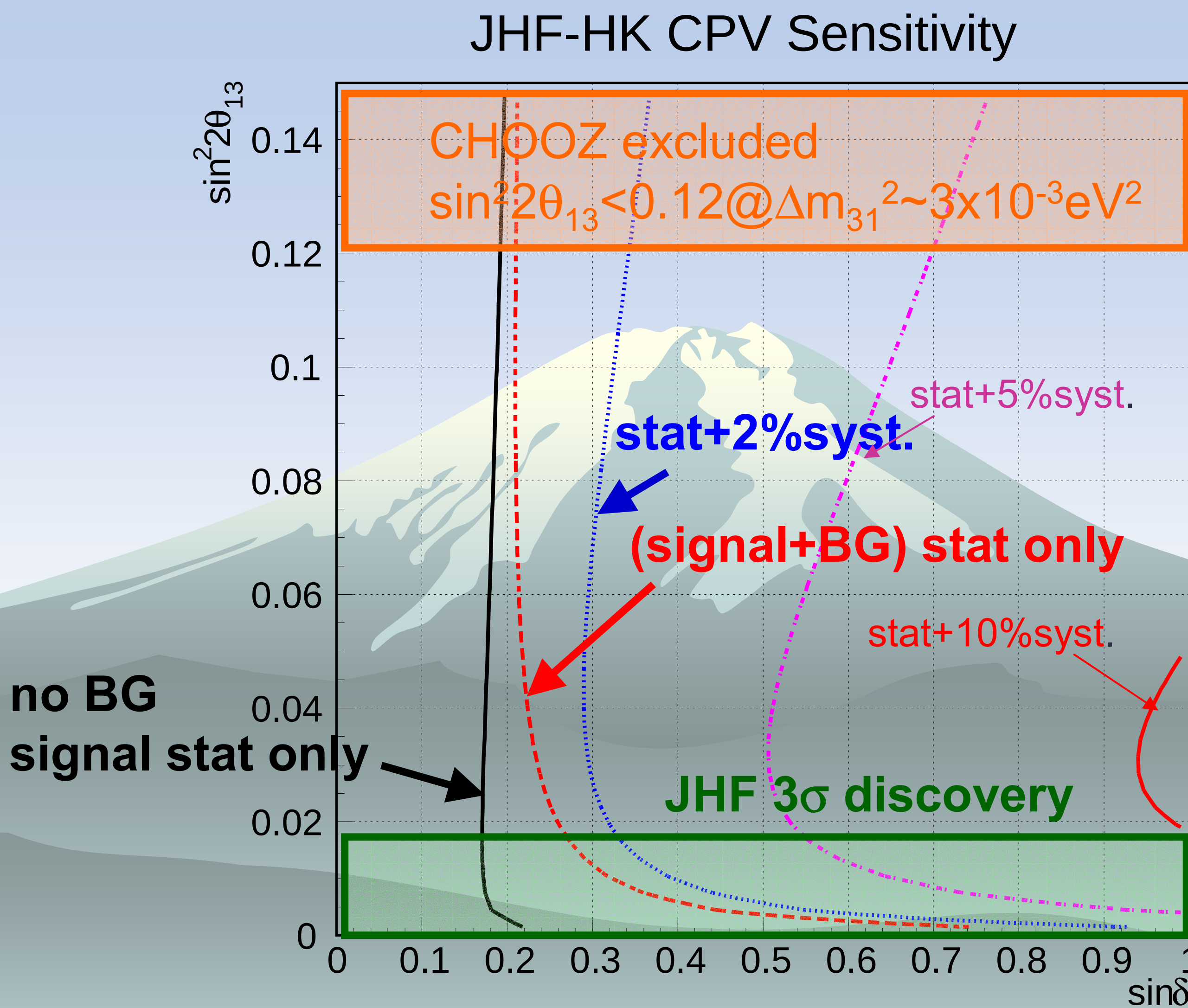


$\delta(\sin^2 2\theta) \sim 0.01$ in 5 years

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

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

CPV sensitivity (3σ) at J-PARC

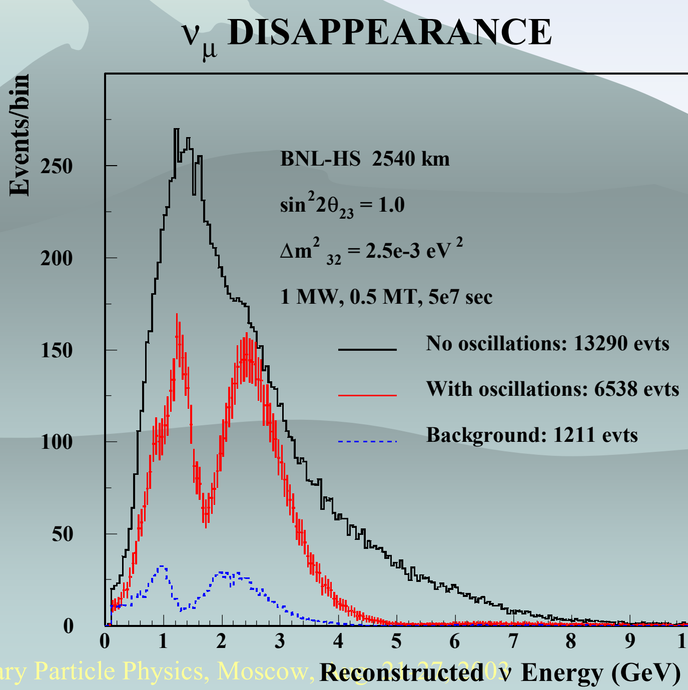


3σ CP sensitivity : |δ|>20° for $\sin^2 2\theta_{13}$>0.01 with 2% syst.

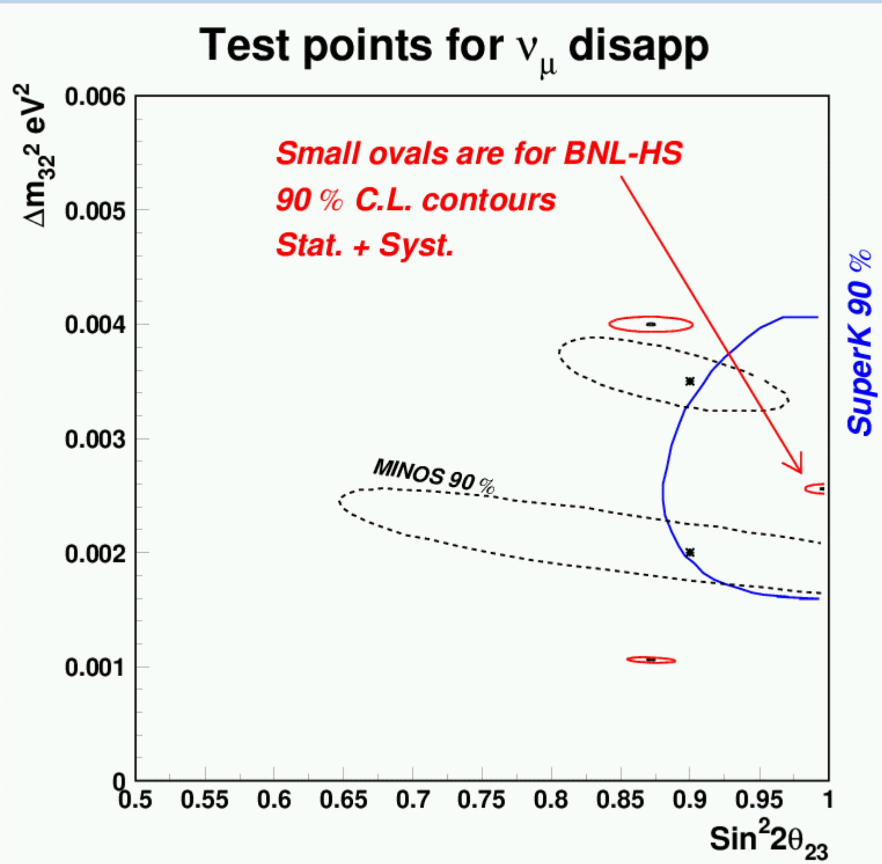
(Ref: Diwan et al., PRD68, 012002, 2003)

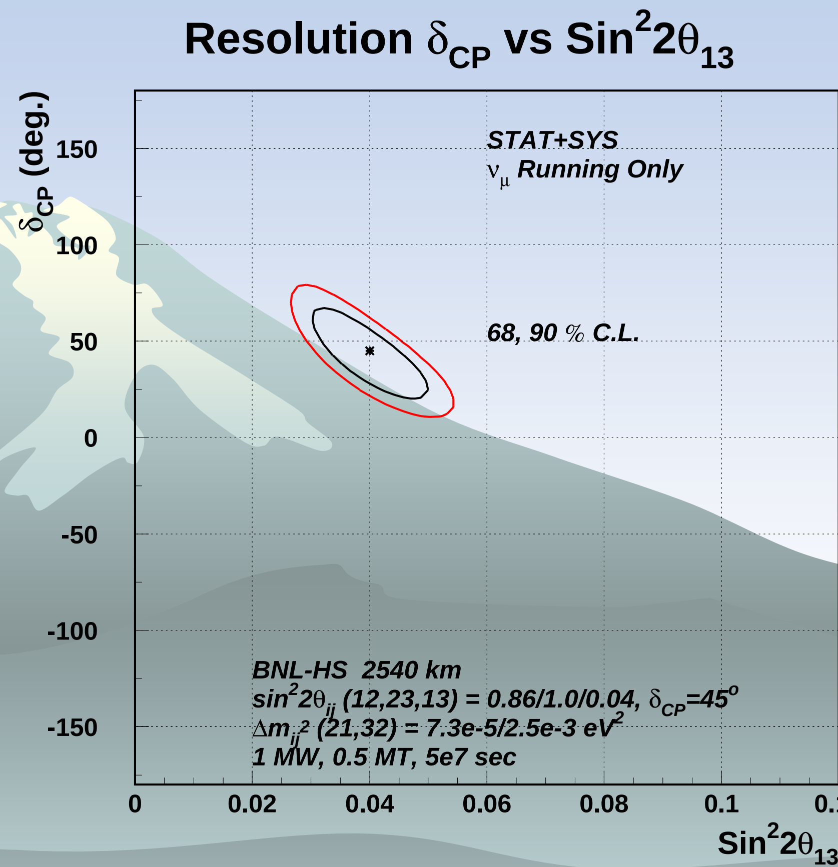
BNL ν project

- Goals
  - Precision measurement
  - ν_e appearance
  - θ_{12}, Δm_{12}
  - Sign of Δm_{23}
  - CPV
- 28GeV upgraded AGS (1MW)
- Conventional horn-focused wide band beam
- 500kt water Cherenkov @ Homestake (2540km)



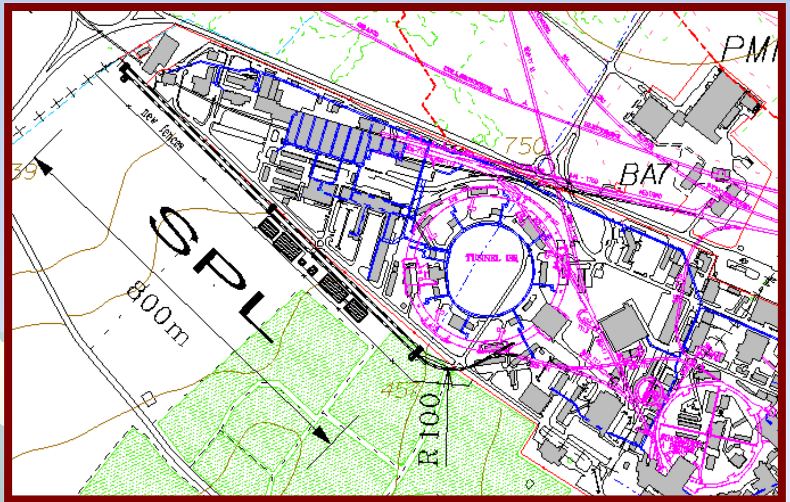
Sensitivities of BNL-ν project

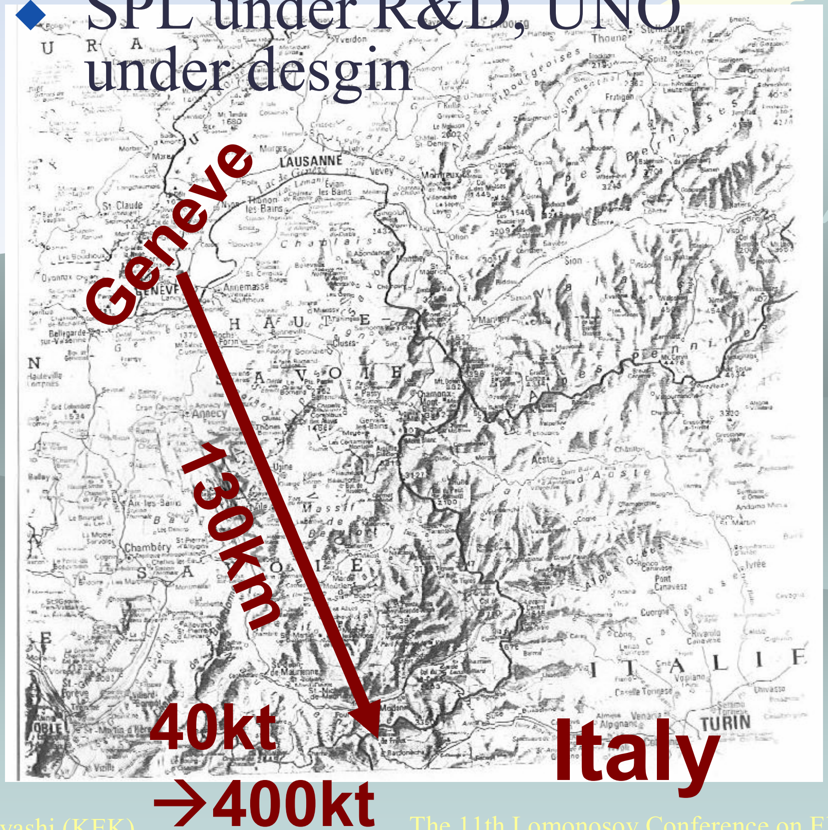


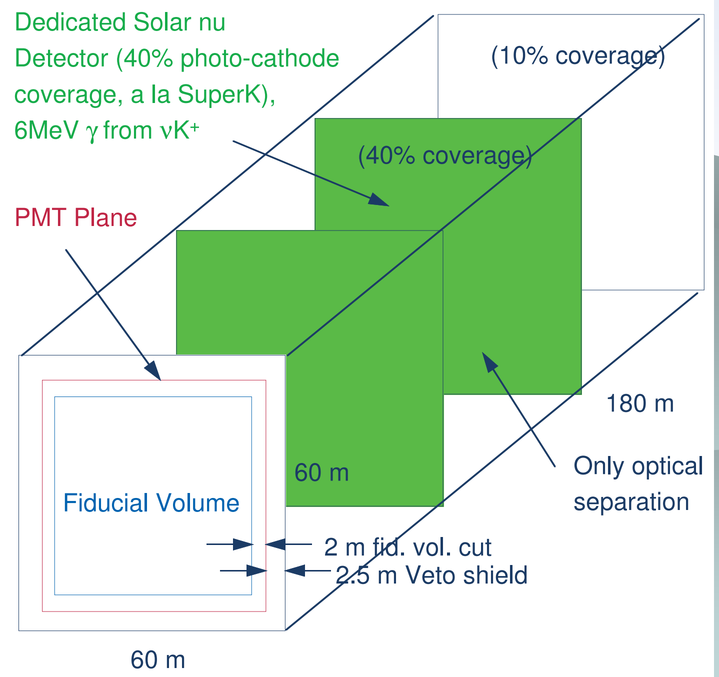


Europe: SPL→Furejus

- 4MW Super Proton Linac (SPL) @ CERN
- SuperBeam/Beta beam
- Water Cherenkov
  - 40→ 400kt (UNO)
- SPL under R&D, UNO under desgin





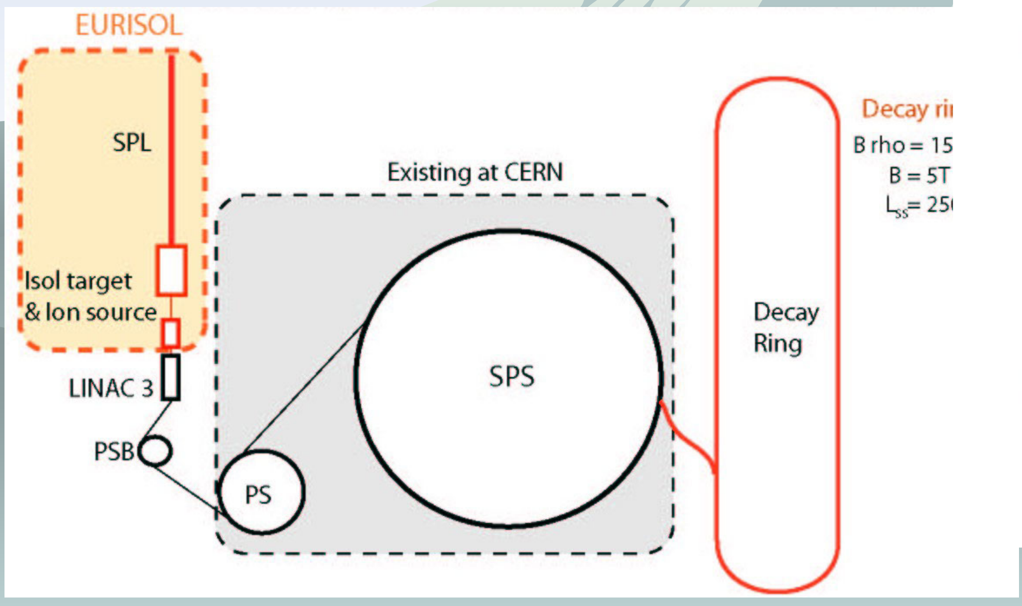


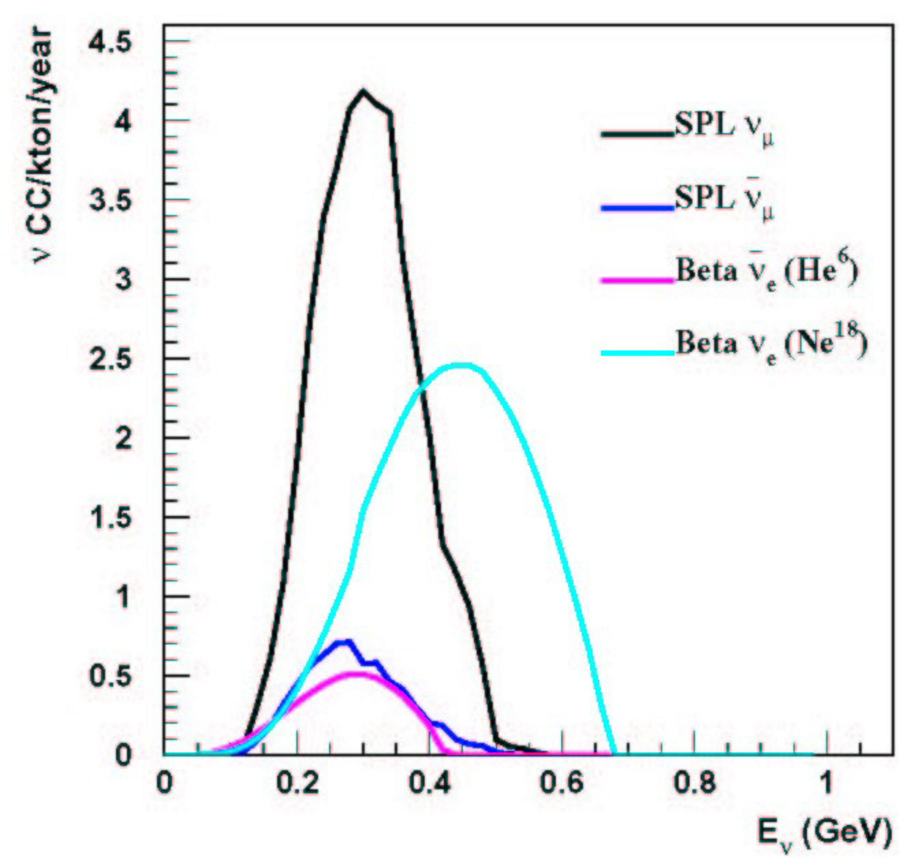
Beta Beam (P. Zucchelli: Phys. Lett. B532:166, 2002)

M. Lindroos and collaborators, see http://beta-beam.web.ch/beta-beam

High energy Pure ν_e beam

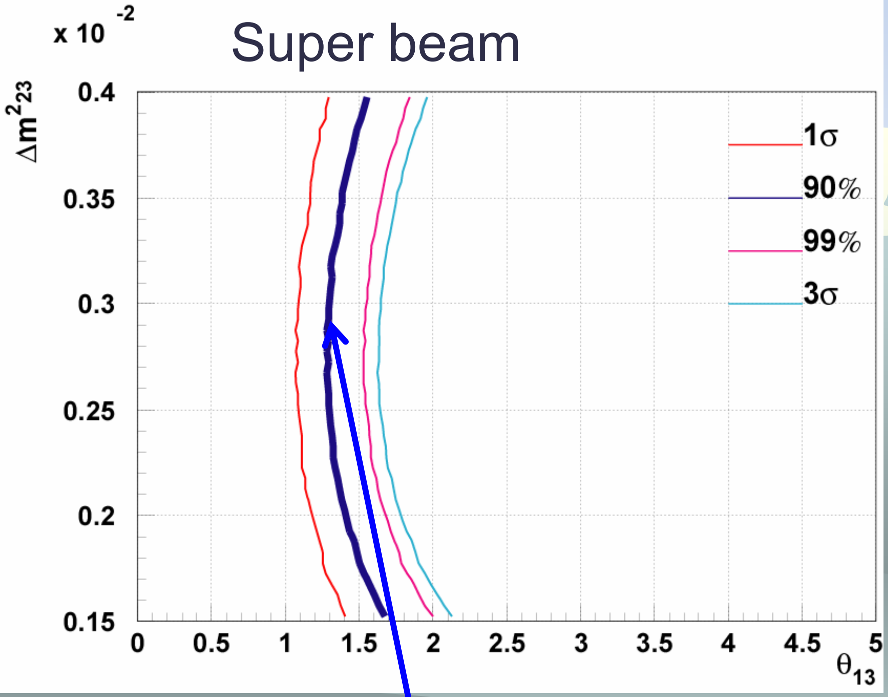
- Accelerate & store radio isotope





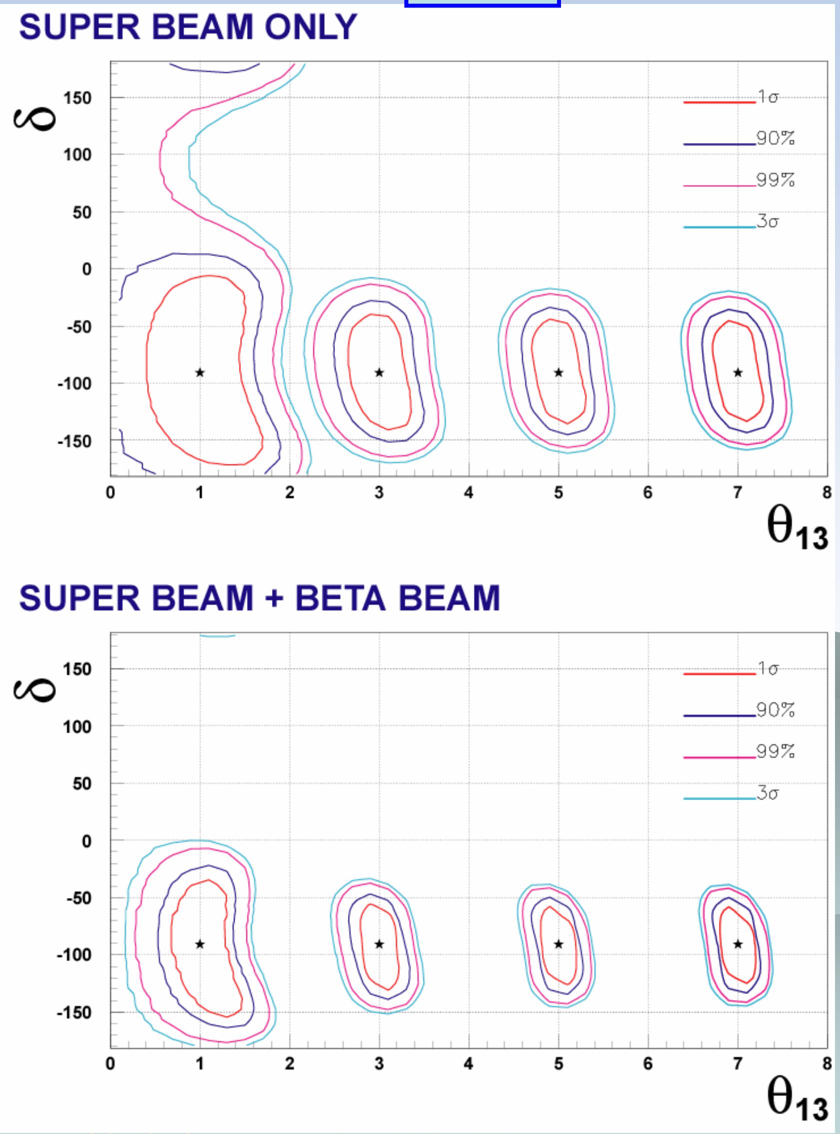
SPL Super/Beta beam sensitivities

ν_e appearance



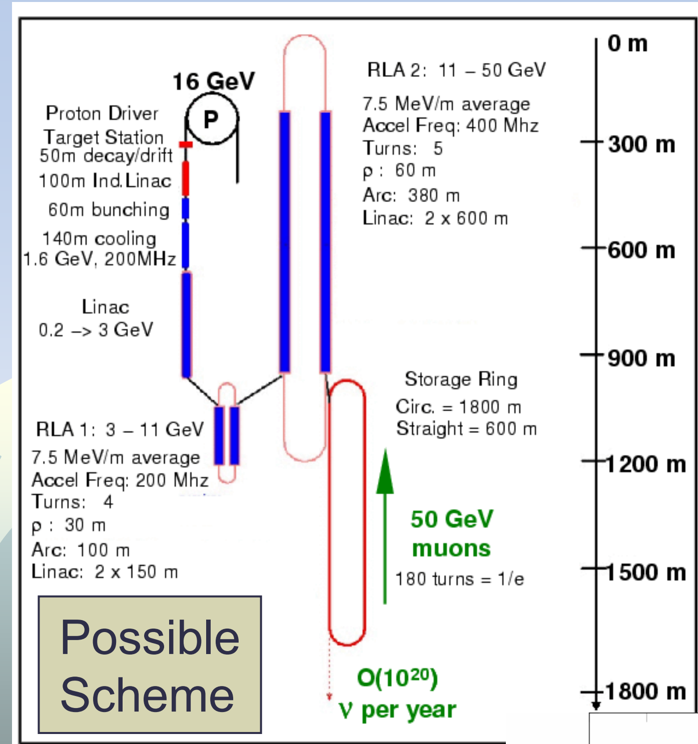
$\sin^2 2\theta_{13} > 0.003$ @ 90%CL

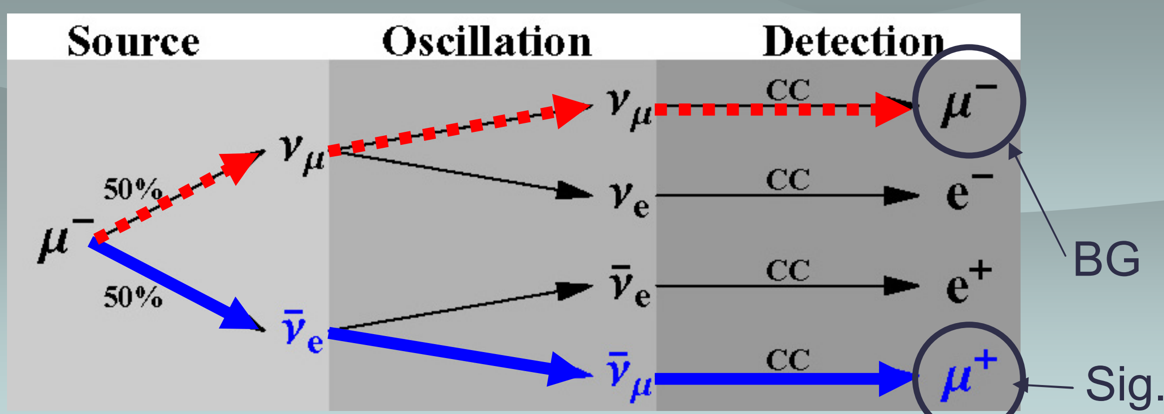
CPV

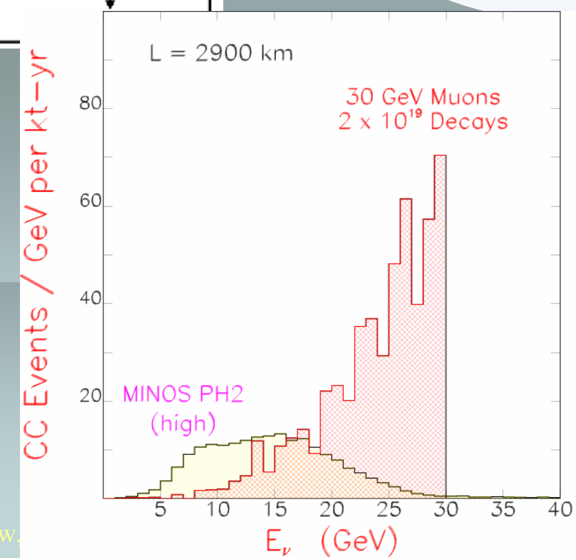


Neutrino factory

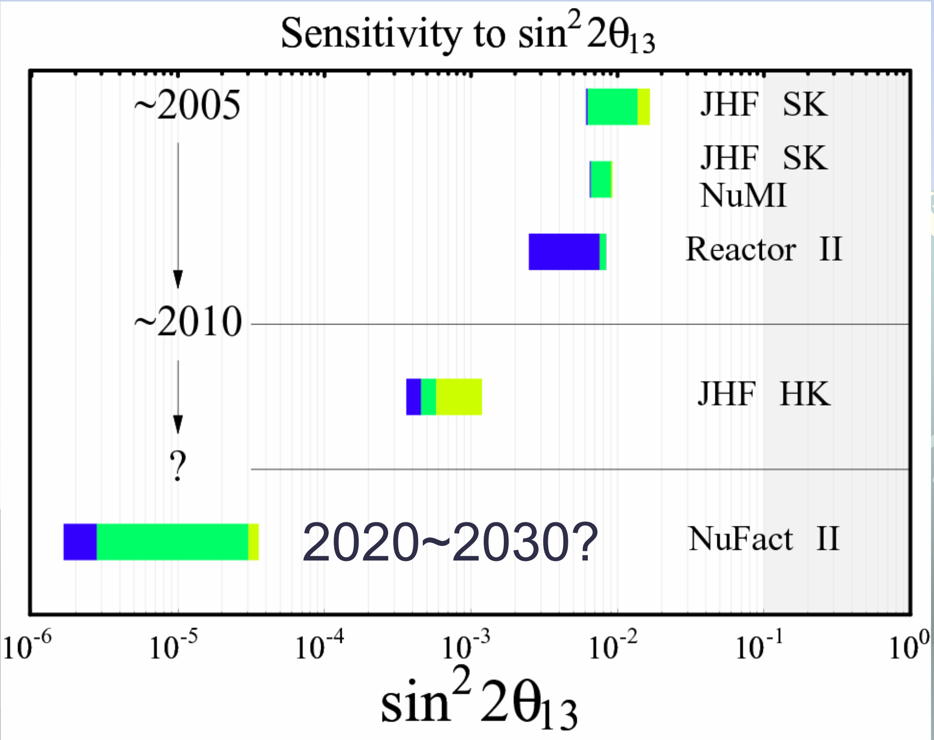
- High energy ν_μ/ν_e beam from muon storage ring
- No uncertainty in neutrino spectrum/flavor content
- Long baseline
- High statistics
- Oscillation signature
  - $\nu_e \rightarrow \nu_\mu$
  - Wrong sign muon
- Large magnetized detector
- Large matter effect
- Technology to be established

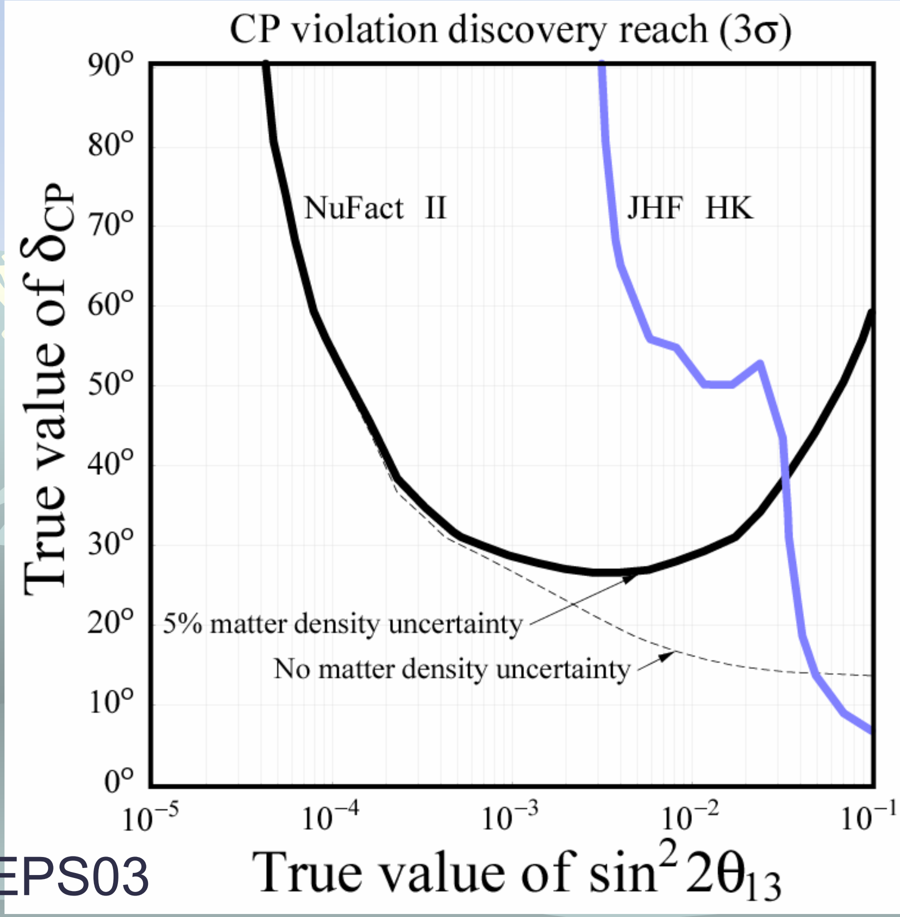






Sensitivities of νFact





P.Huber @ EPS03

νFact could extend sensitivities dramatically,
but first need to establish component technologies one by one

Possible time line

- Near future (within 2~3years)
  - 1st phase experiments
    - Final results from K2K (2005)
    - MINOS(2005)/CNGS(2006)
- Medium near future (4~10yrs?)
  - J-PARC – SK (2008?~)
  - NuMI-OA (2008?~)
- Future (10~15years) w/ Mton detectors
  - J-PARC – HyperK (2013?~)
  - BNL ν
  - SPL (Beta beam?) -- Furejus (Mton)
- Far future (>20~30yrs)
  - Neutrino factory

Summary

- K2K: The first (only running) LBL experiments
  - Established methodology of LBL experiments
    - Beam direction(GPS survey..), stable operation, event selection
  - ν_μ disappearance:
    Osc. prob >99%, $\Delta m^2=1.5\sim3.9\times10^{-3}eV^2$
  - NEW ν_e appearance:
    $\sin^2 2\theta_{\mu e}<0.15$ @ $\Delta m^2=2.8\times10^{-3}eV^2$
- MINOS(2005), OPARA/ICARUS(2006) coming soon
- Next generation LBL experiments
  - Discovery/measurement of θ_{13}, δ
  - Precision measurements of oscillation parameters
  - J-PARC neutrino experiment submitted 4yrs budget request
- The "neutrino flavor physics" have just started
  - there should be plenty of enjoyable discoveries / surprises