Future Accelerator Experiments

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Abstract

Discuss the next steps in neutrino oscillation experiments and the likely development of the field in the mid- and long-term future

One Day IOP/CfFP Meeting on Neutrinos: RAL, 29-6-05

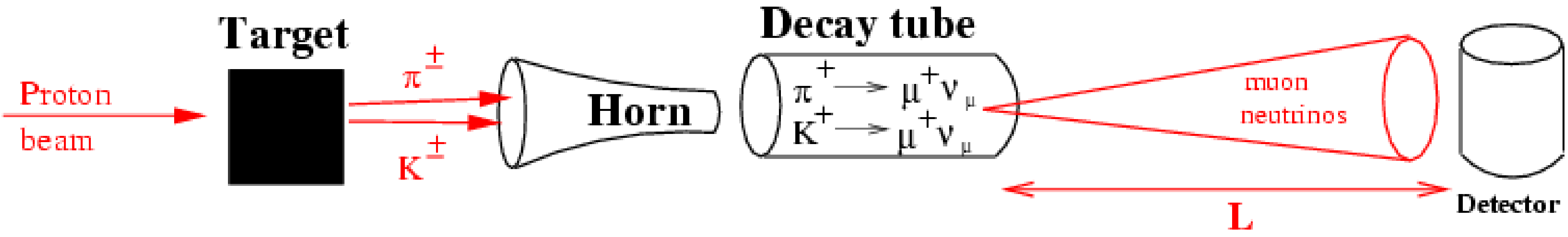
Introduction

- Oscillation scale set by:

$$\frac{\Delta m^2 L}{E_\nu} = \frac{\pi}{2}$$

- Atmospheric oscillations, with $\Delta m^2 \sim 3 \times 10^{-3}\,\mathrm{eV}^2$, suggest baselines $[10km, few \times 1000km]$ for E_ν $[0.1GeV, few \times GeV] \Rightarrow$ Earth-based experiments to probe $\nu_\mu \rightarrow \nu_X$ (N.B. solar oscillation baselines too long)
  - Leading oscillation parameters: $\theta_{23}, \Delta m^2_{32}$ from ν_μ-disappearance from a ν_μ accelerator beam
  - Sub-leading oscillations: $\nu_\mu \rightarrow \nu_e$ appearance sensitive to θ_{13}
  - MSW matter effects give sensitivity to $sign\left(\Delta m^2_{13}\right)$
  - Comparing $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ is sensitive to CPV δ

Conventional Neutrino Beam



- Big advantage over atmospheric/solar experiments: control of the beam contents/energy/luminosity

- Two approaches,
  - Narrow Band Beams: Select single π momentum magnetically or off-axis angle - either way you loose flux. But reduced backgrounds for ν_e appearance generally more sensitive limits per MW*kton
  - Broad Band Beams: Can map out the shape of oscillations vs E_ν, higher event rates but also higher backgrounds.

How?

- Make your beam of ν_μ
- Look for ν_μ disappearance from the beam by forming,

$$\frac{\mathrm{E}_\nu\,(\text{detected})}{\mathrm{E}_\nu\,(\text{expected, with no oscillations})}$$

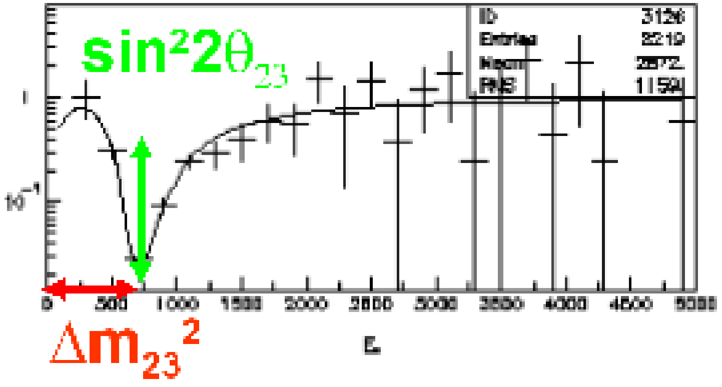
Challenge: Controlling the error on the denominator

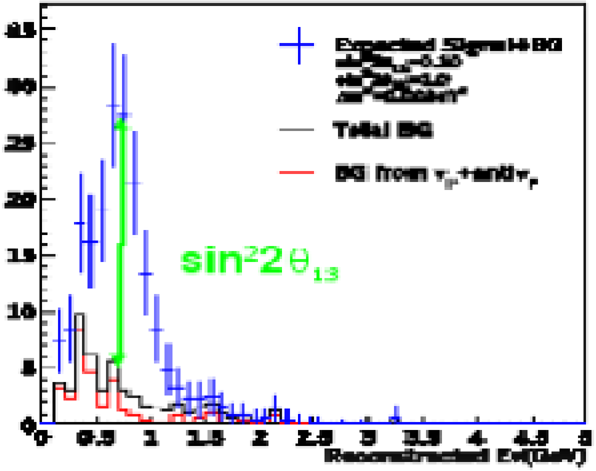
- Detect $\nu_\mu \longrightarrow \nu_e$ appearance signal

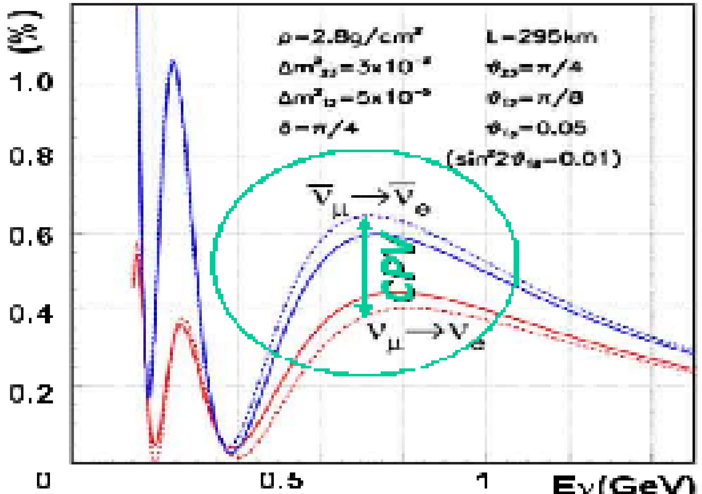
Challenge: Evaluating the background

- Comparing ν to $\bar{\nu}$:

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

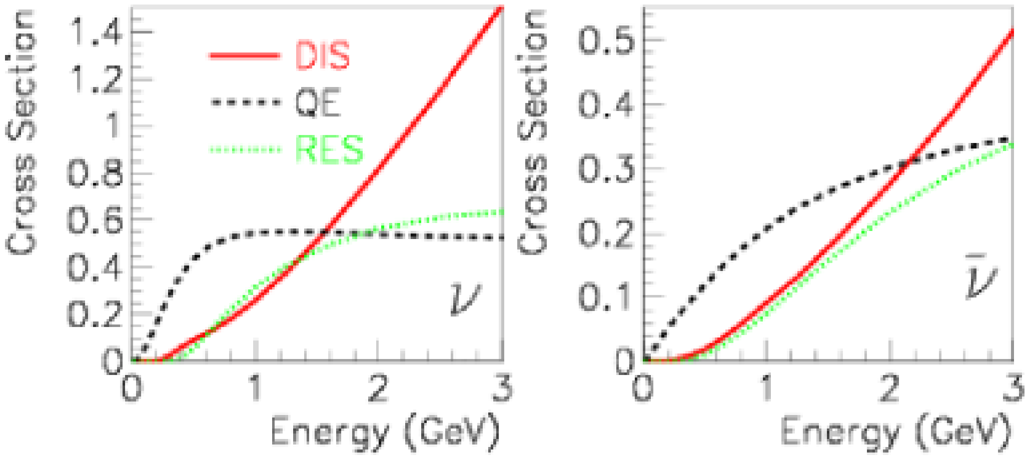






Detector Options

- Must detect ν-CC processes (NC are flavour-blind)



- $E_\nu < 1$GeV quasi-elastic scattering(CCQE) dominates

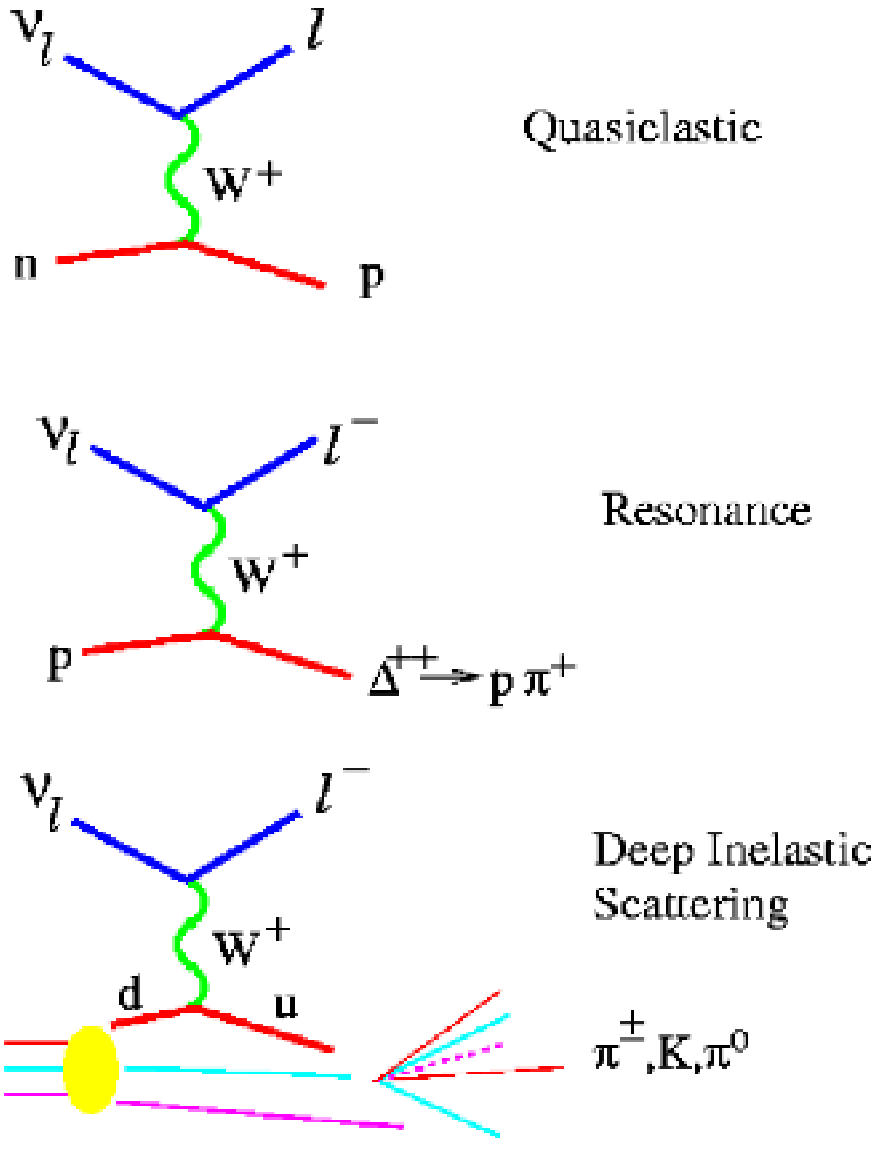
  $\Rightarrow$ water Cerenkov detectors suitable

- By $E_\nu \sim 2$GeV considerable contribution from inelastic scattering

  $\Rightarrow$ need to measure energy of hadronic part of cross section

  $\Rightarrow$ low-Z hadron calorimeters (e.g. scintillator) suitable

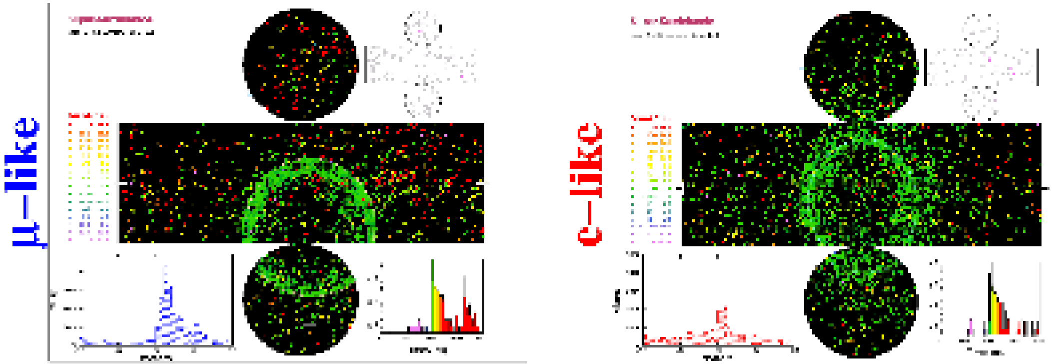
- Liquid argon TPC: can be used from MeV to many GeV



(D.Harris, NuFact04)

Water Cerenkov

- Excellent e/μ separation for clear single-ring events



(SuperK event displays: Mark Messier)

- Excellent CCQE E_ν resolution from simple kinematics:

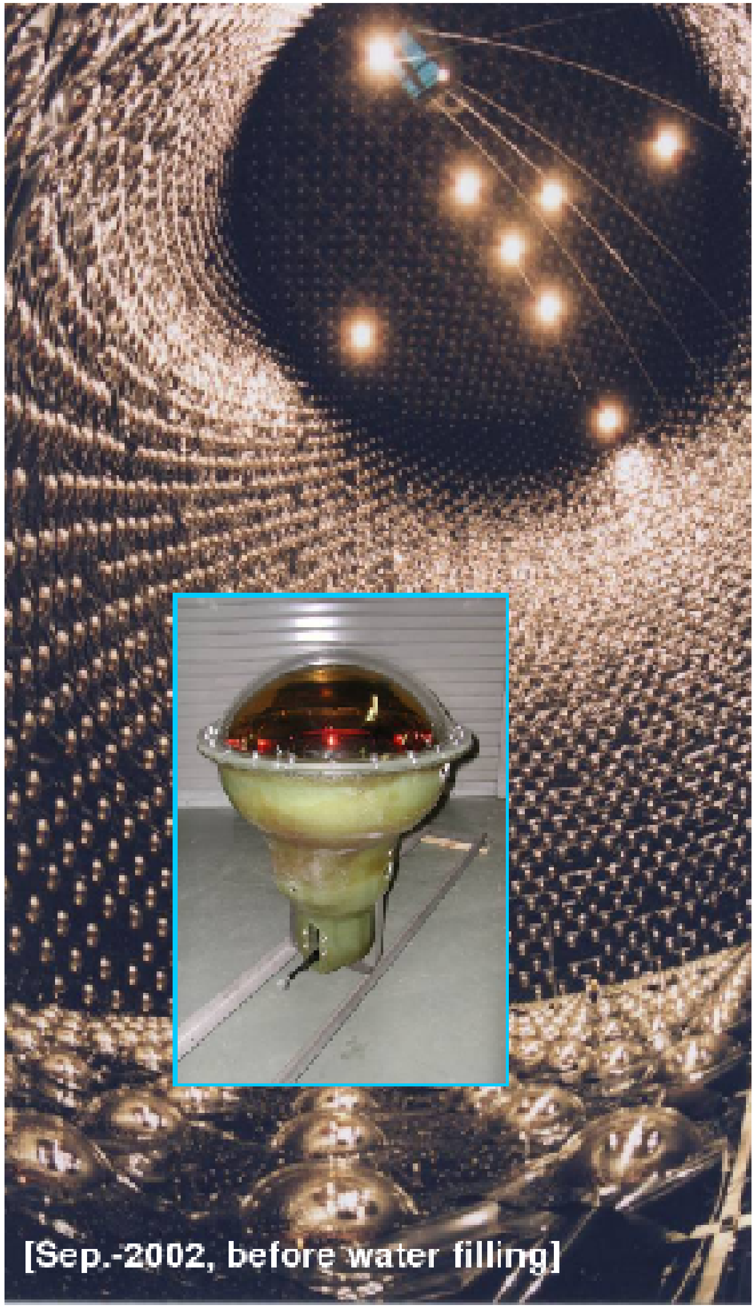
$$E_\nu \quad = \quad \frac{m_n E_\ell - m_\ell^2/2}{m_n - E_\ell + p_\ell \cos\theta_\ell}$$

(N.B. the recoil proton is below $\check{C}$erenkov threshold for detection)

- SuperK most massive ν-detector to date

  $(22.5$kT fiducial volume)

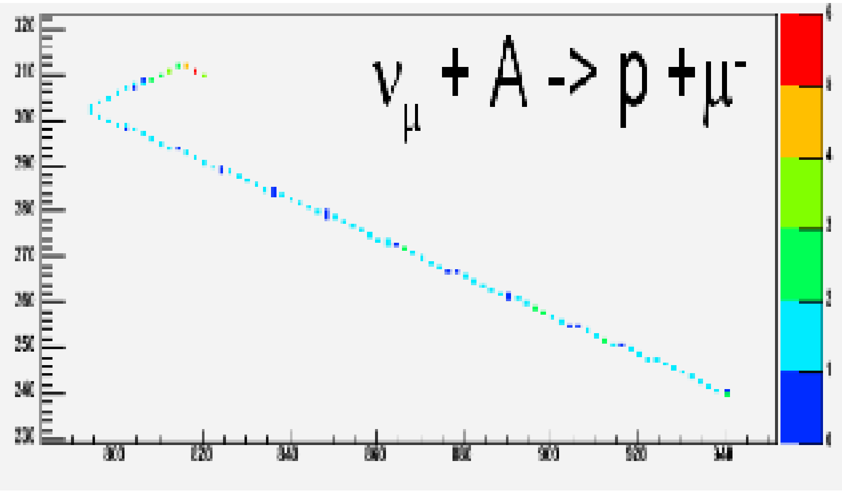
- Multi-ring events more problematic

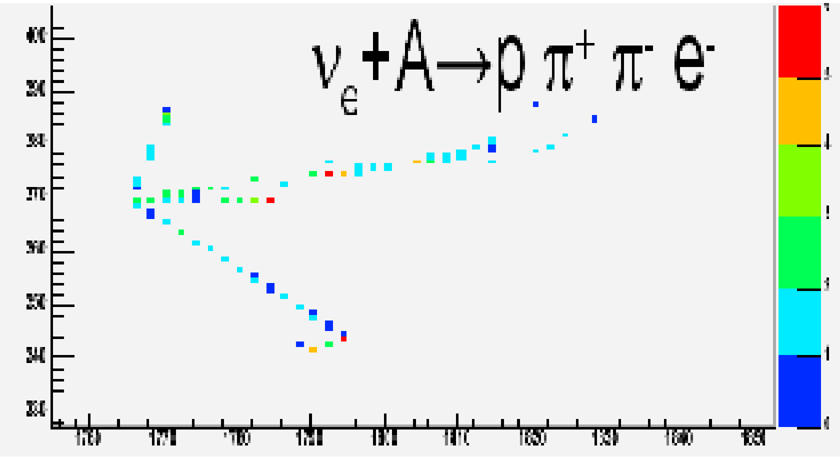


[Sep.-2002, before water filling]

Scintillator Calorimetry

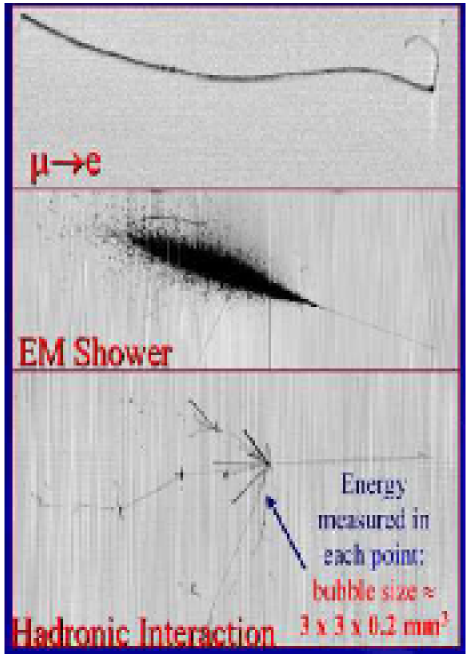
- Can reconstruct multiple particle event topologies $\Rightarrow E_\nu$ resolution is good over wide range
- e/γ separation by looking for gaps after event vertex
- e/μ separation from track characteristics
- Good value physics performance/per £

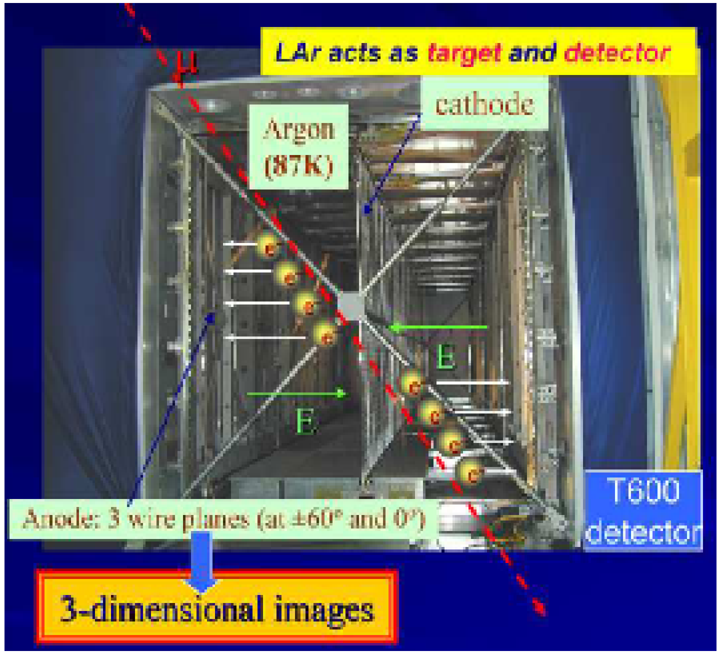




Liquid Argon TPC

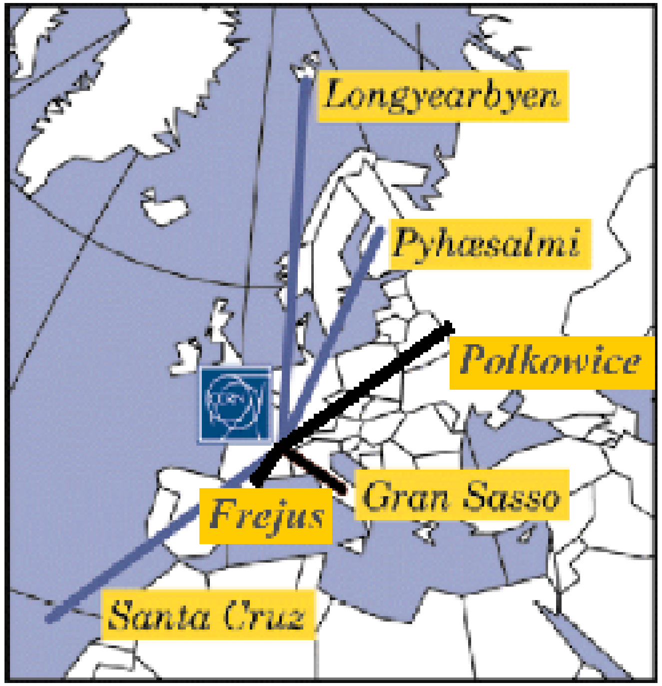
- Now a mature technology giving bubble chamber-like reconstruction
  - 3D-tracking and full-sampling calorimetry
  - Excellent energy/angular resolution over broad energy range
  - μ, K, p particle-ID by dE/dx
  - Can embed in magnetic field for charge discrimination of μ, e
  - Possibility of charge, scintillation and Čerenkov-light readout
- **ICARUS T600** ready for physics at Gran Sasso by end of this year ('passed brilliantly' commissioning tests - A. Rubbia)
- Very modular for large-scale coverage (T3000)

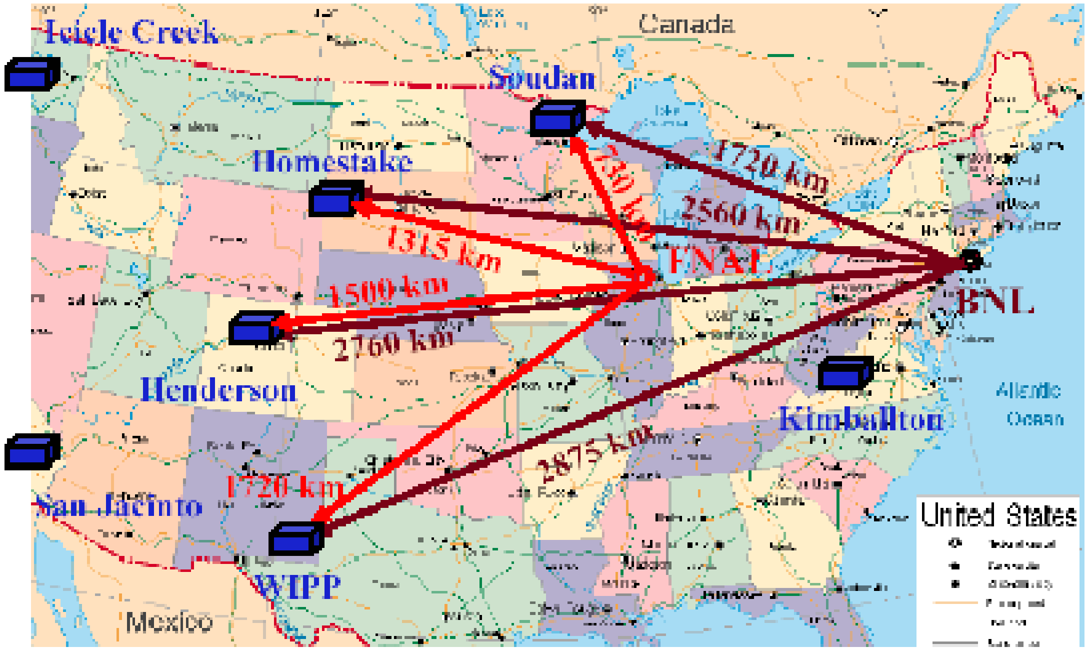


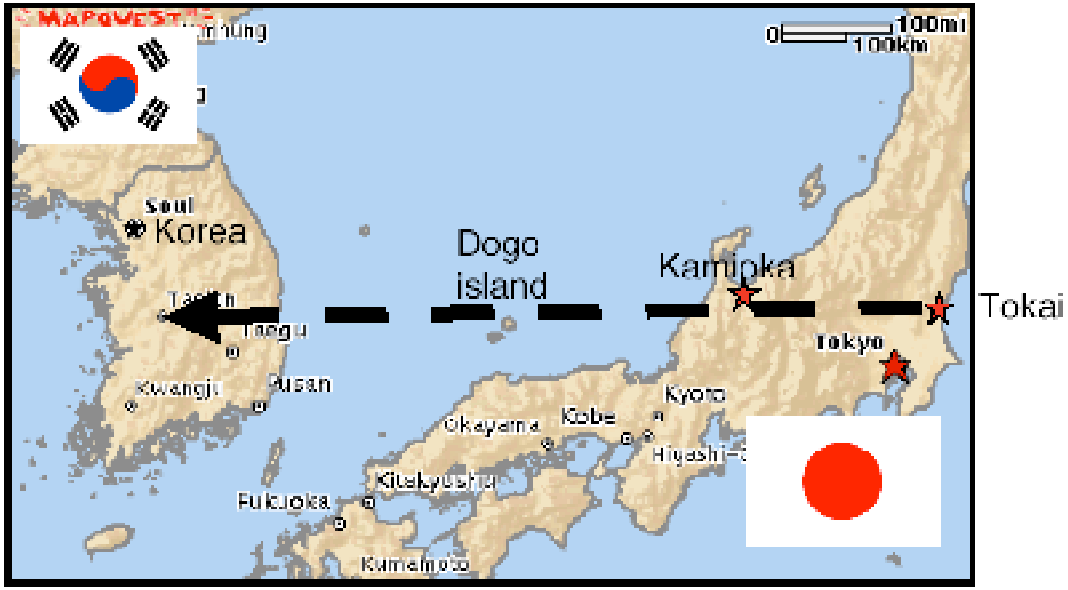


A. Rubbia, NuFact04

Facilities Worldwide







Currently Running or About to Run

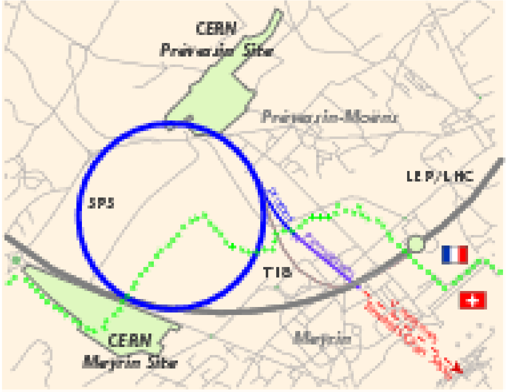
- K2K

- MINOS

- CNGS: CERN ν_μ beam to Gran Sasso(4.5×10^{19} POT/year), to verify leading oscillation is to ν_τ.

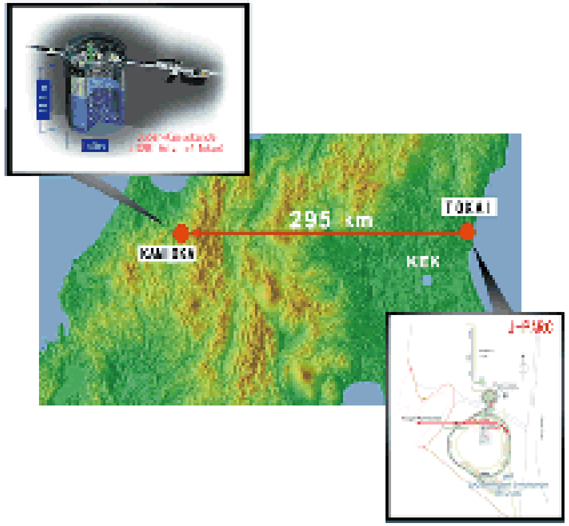
  Far detectors: OPERA (emulsion cloud chamber) and ICARUS (Liquid Argon TPC).

  Beam ready 2006 with partially complete detectors



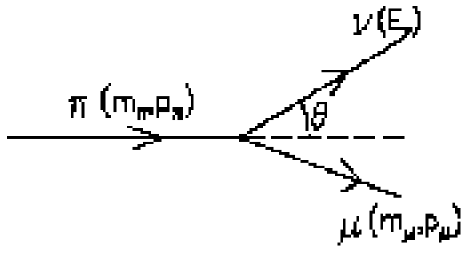
In Search of θ_{13}: Superbeam Experiments

Existing oscillation experiments have limited sensitivity to θ_{13}. To go further requires the next generation of 'superbeam' experiment (T2K, NOνA):

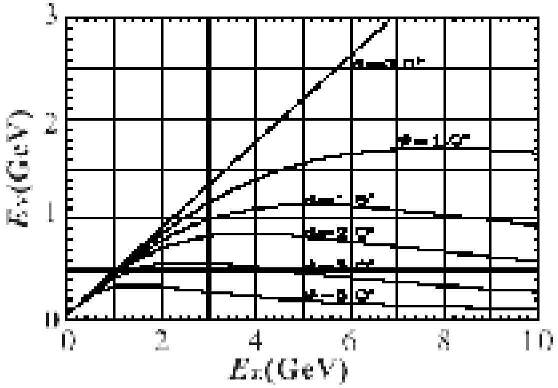


- Looking for $\nu_\mu \longrightarrow \nu_e$ appearance
- High intensity proton drivers (100'skW to MW) producing 'Superbeams'
- Off-axis beams with tuned beam energy
- Near and far detectors

Off-Axis Narrow-Band Beam

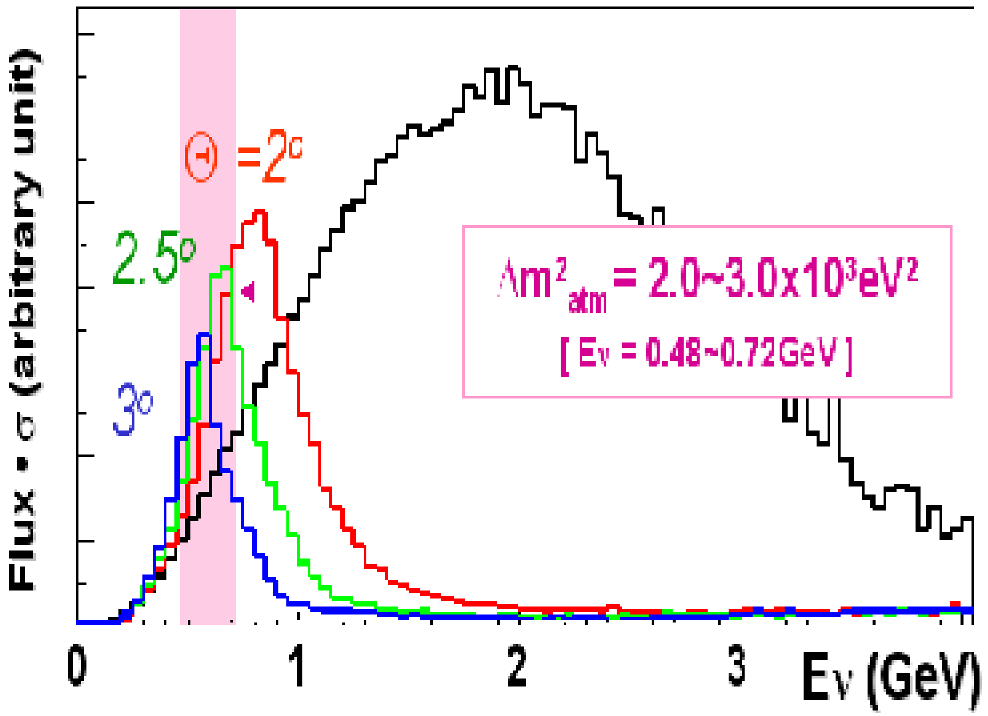


$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$



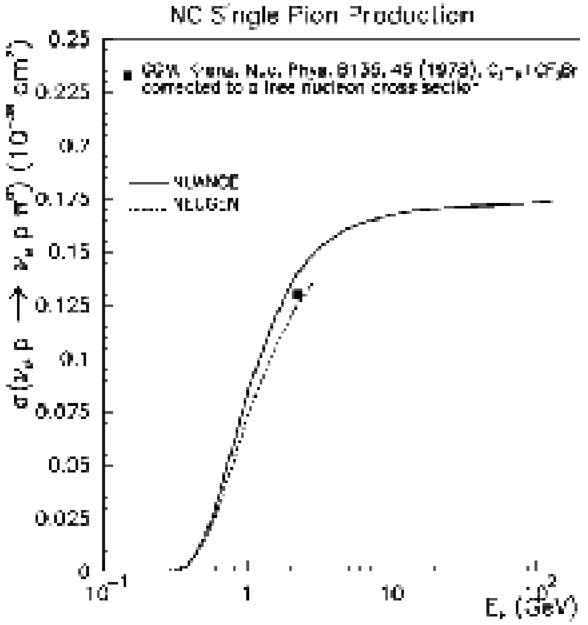
- Tuning the angle, tunes the energy to sit at oscil. prob. maximum (but precise beam monitoring becomes important!)

- Cutting out high energy tail of flux reduces $\pi^\pm, \pi^0$ produced in inelastic collisions:
  - Improves $\sigma(E_\nu)$ since π can get mistaken for μ in QE events
  - Reduces the π^0 background to ν_e appearance



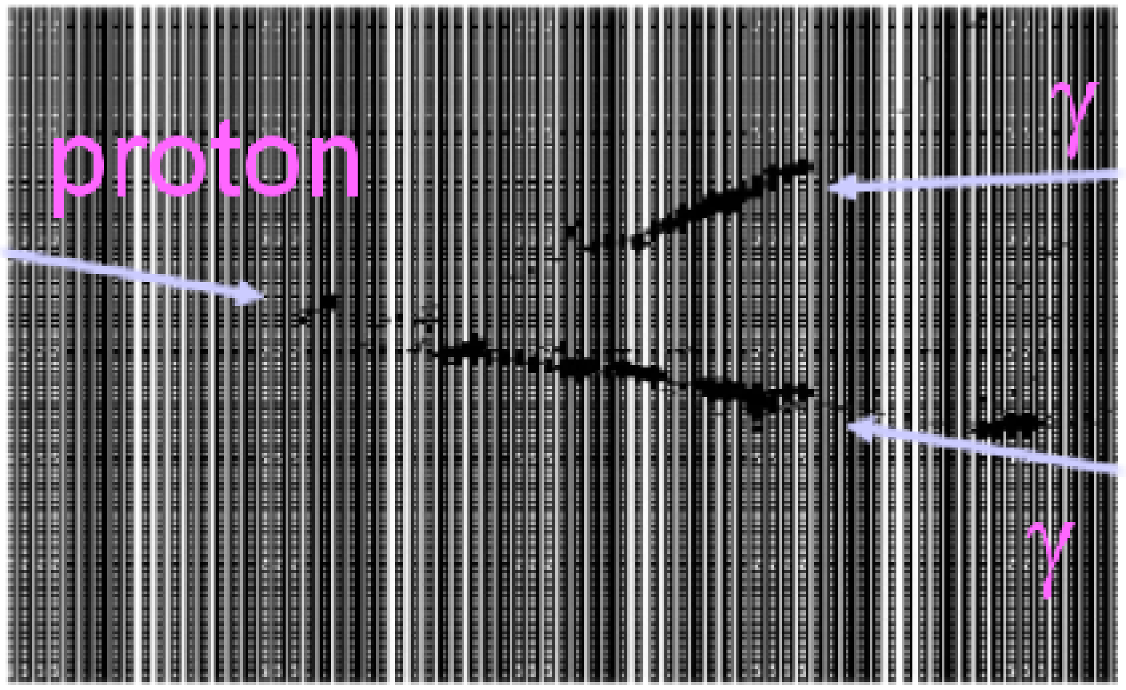
Near Detectors

- ν_μ Disappearance: can't rely on calculations/Monte Carlo simulations to give you the denominator (non-oscillated event rate)
  ⇒ need to measure signal flux and cross sections
- ν_e Appearance: background cross sections poorly known
  ⇒ measure background cross sections
  e.g. NC single-π^0 production



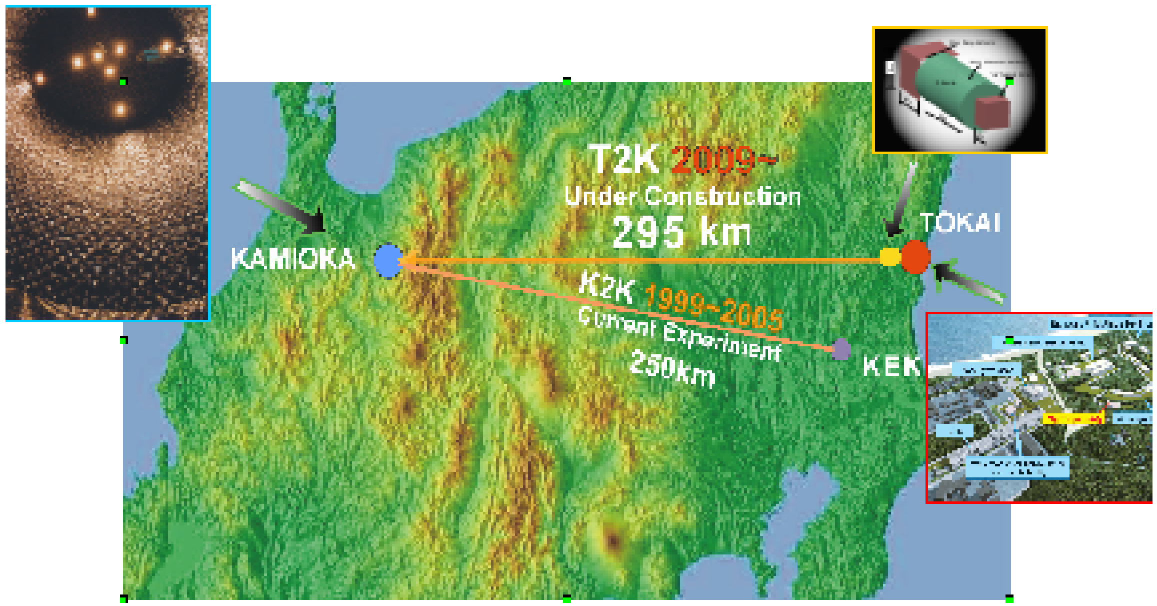
(G. Zeller, hep-ex/0312061)

Measurements from fine-grained Near Detectors are essential

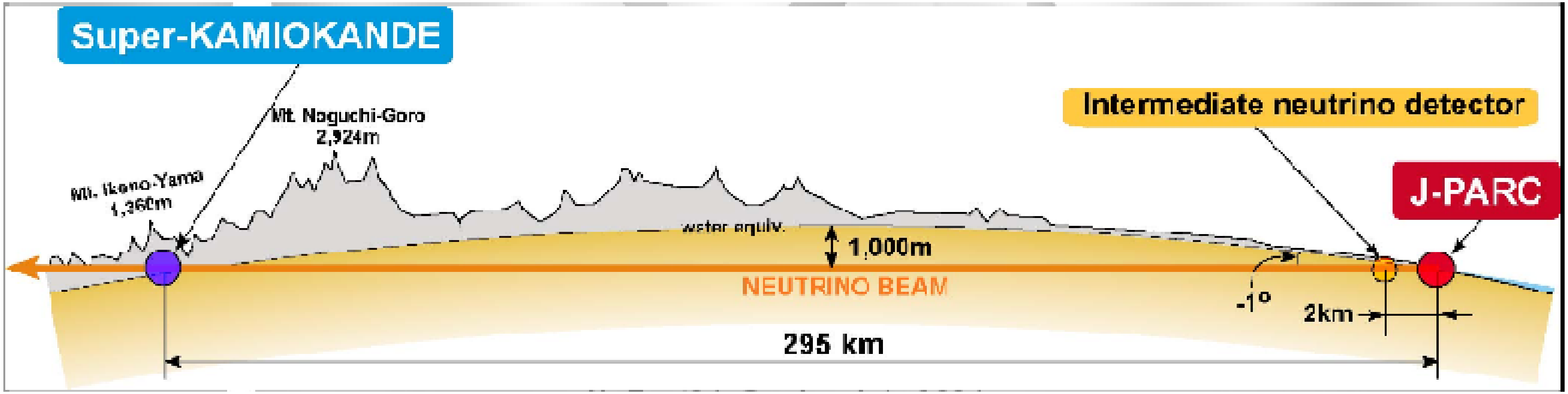


(D. Casper, NuFact04)

T2K Project

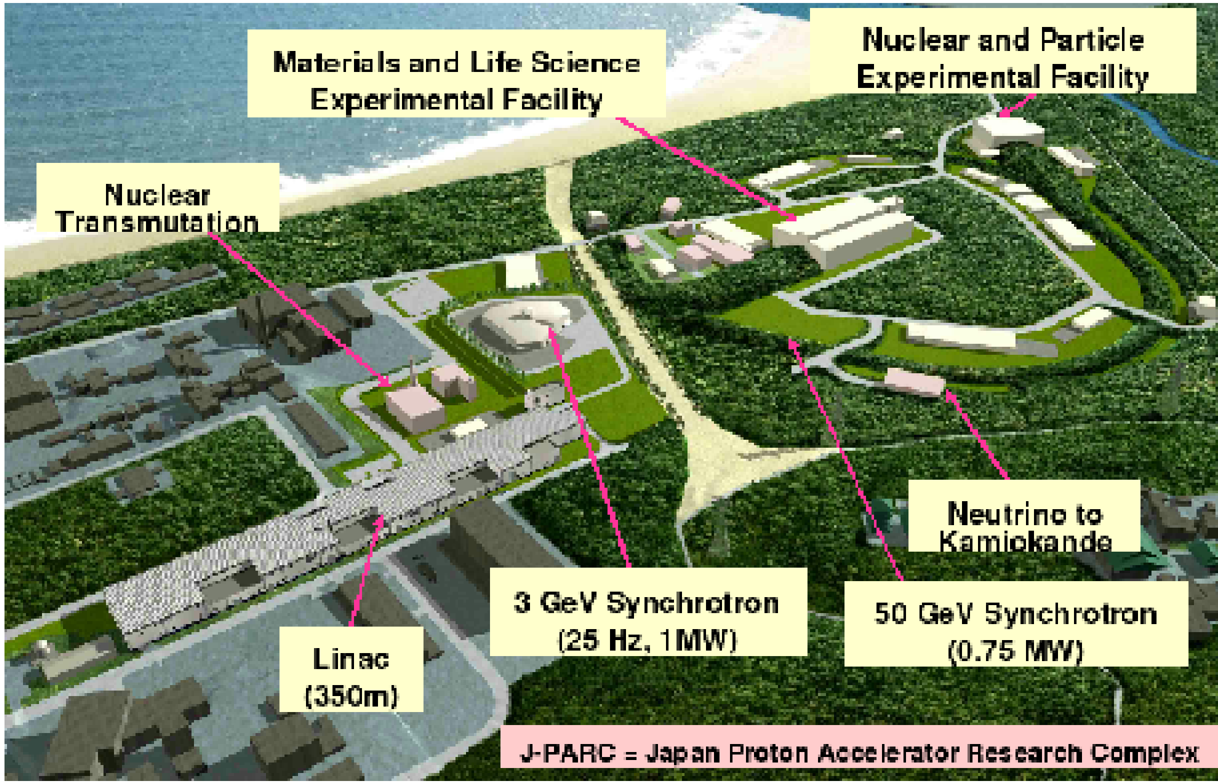


- Fire ν_μ beam from JPARC complex in Tokai, via near detector(s) 295km to SuperK in Kamioka
- $180 project, first beam in April 2009



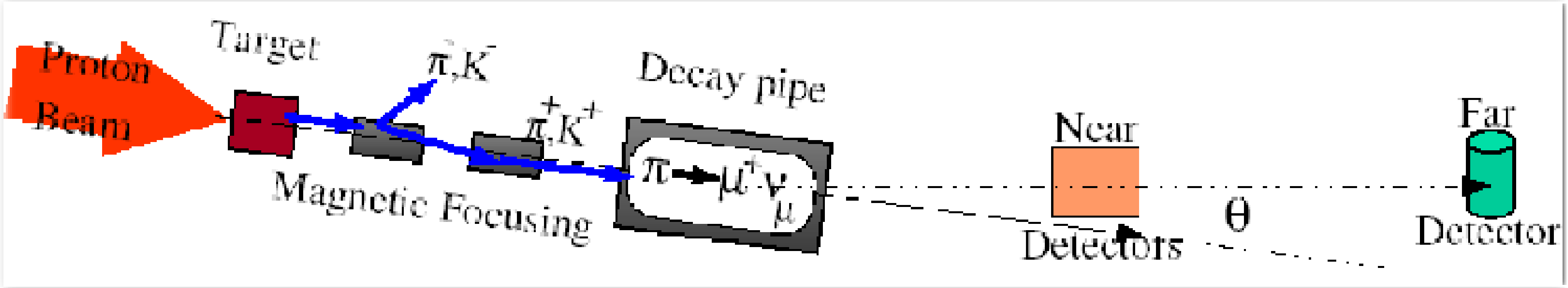
JPARC

- Will be the most intense proton beam ever built
- Nominally a beam power of 0.75MW giving 10^{21} POT/year for 130 days/year of operation
- Plans to upgrade to 4MW

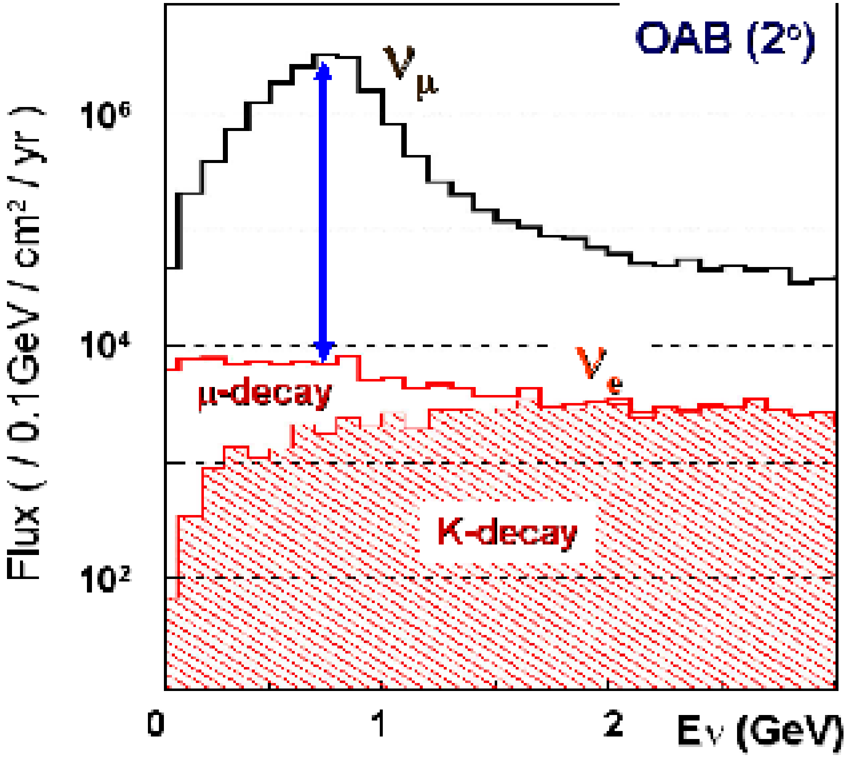


JPARC: Construction

Off-Axis Configuration

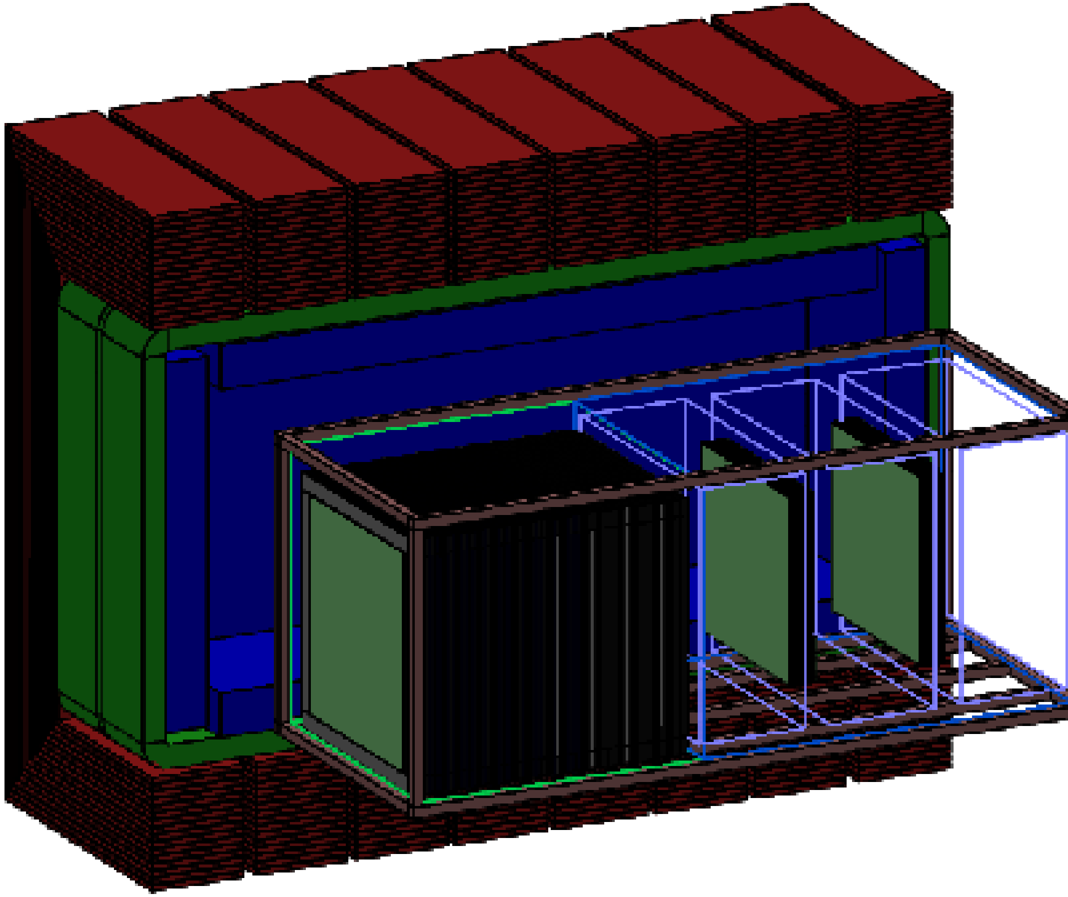


- Off-axis angle of $2.5°$ matches baseline of 295km
- ν_e contamination of ν_μ beam is about 1% from μ decay ($E < 1$GeV) or $K^0, K^\pm$ decay ($E > 1$GeV)



Near Detector

- Sited 280m from the target sitting inside the **UA1** magnet!
- Largely a pre-radiator(iron)/scintillator sandwich
- Design split into 2 main functions:
  - Scint. sandwich+ **ECAL** optimised to measure the π^0 rate (**'P0D'**)
  - **Upstream** 'Tracker' which includes **TPC's** to trace **CC** μ and e
- **Large water content** (water-based scintillator and passive water targets) to reduce error comparing measurements in scintillator to **water** of **SuperK**



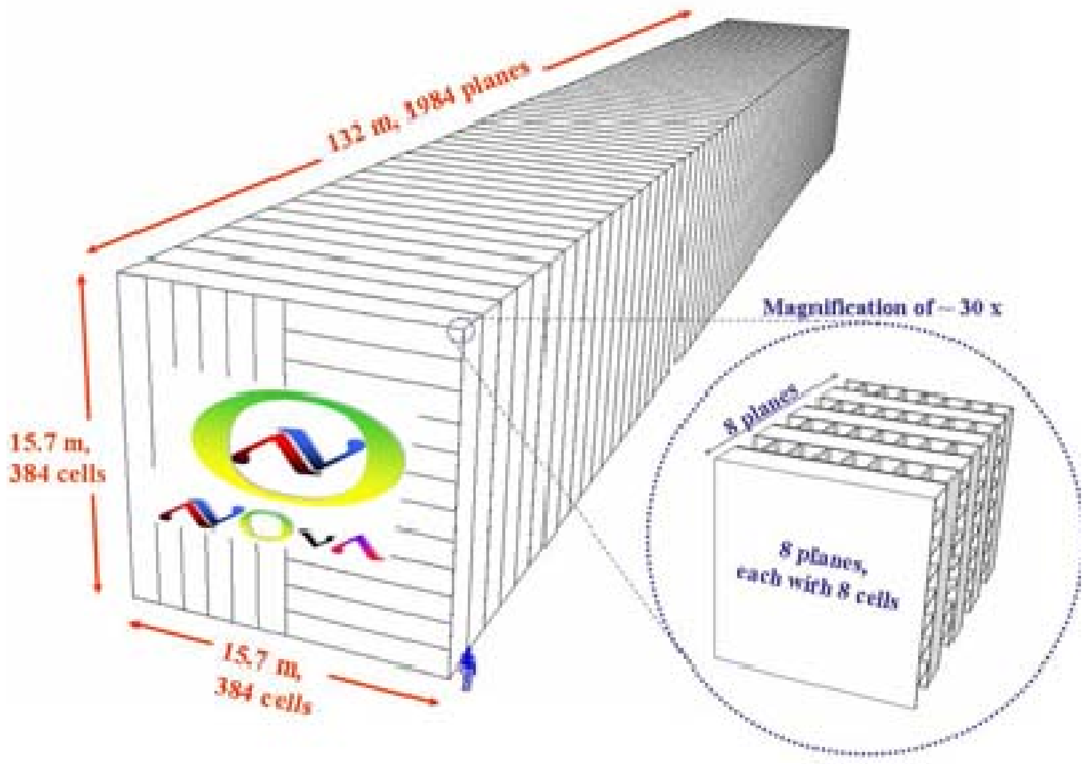
European project with the **UK** heavily involved:

ECAL,optical sensors, light calibration system,electronics+**DAQ**, mechanical engineering + ...

(**Imperial**,**Lancaster**,**Liverpool**,**QML**,**RAL**, **Sheffield**,**Warwick**)

NOνA

- An 'off-axis' MINOS experiment using the same NuMI beamline
- Situated at Ash River MN, $L = 810$km
- NoνA is a 30kT liquid scintillator 12km off axis
- Near detector at FNAL $\sim$ 1km from target ('little NoνA' clone)
- Has stage 1 approval FNAL PAC/start 2009?



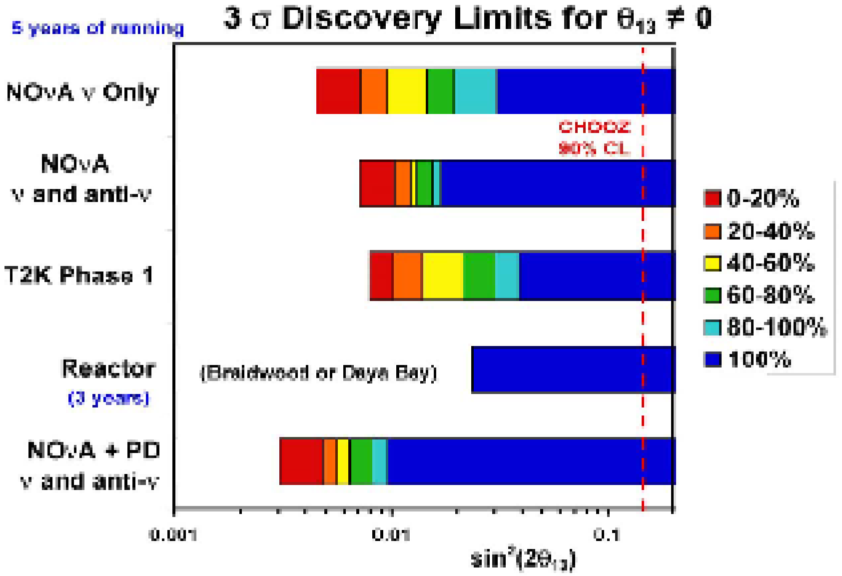
Projected Performance

T2K and NOνA complementary in global quest to find $(\theta_{13}, sign\left(\Delta m^2_{13}\right), \delta)$:

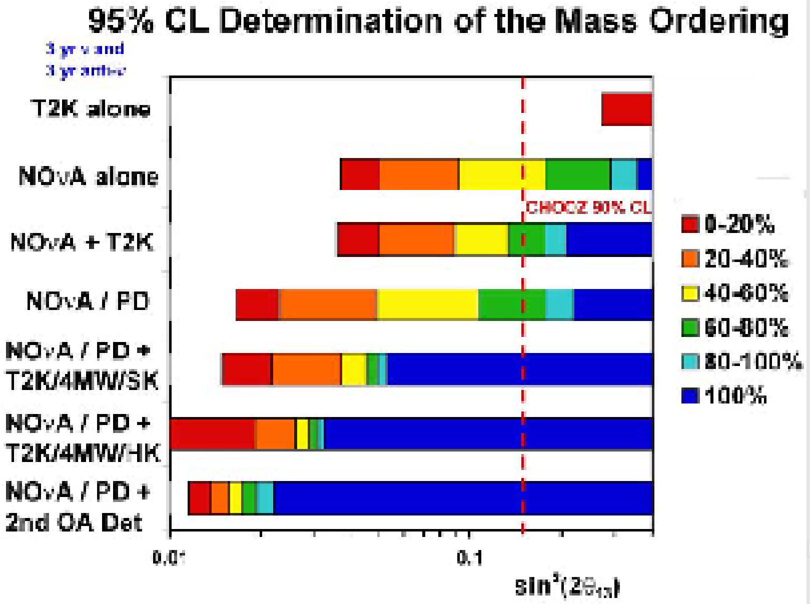
- $\boxed{\theta_{13}}$ individual sensitivities similar $\Rightarrow$ gain from combination
- $\boxed{sign\left(\Delta m^2_{13}\right)}$ NOνA baseline a compromise between θ_{13} sensitivity and increased matter effects. Comparing NOνA to T2K(small matter effects) aids resolution of mass hierachy.
- $\boxed{\delta}$ one experiment running ν_μ and the other $\bar{\nu}_\mu$ the best scenario (useful for θ_{13} and mass hierachy too)

(e.g. Minikata et al. Phys. Rev. **D68, 013010 (2003)**)

(N.B. Take a pinch of salt, (G.Feldman, Win05))



Presented as % coverage in CP phase δ



Next Steps

What if T2K and NOνA don't have the sensitivity to measure θ_{13} ?

Ans: T2K/NOνA upgrades

In general, first-generation Superbeam experiments have poor sensitivity to CPV

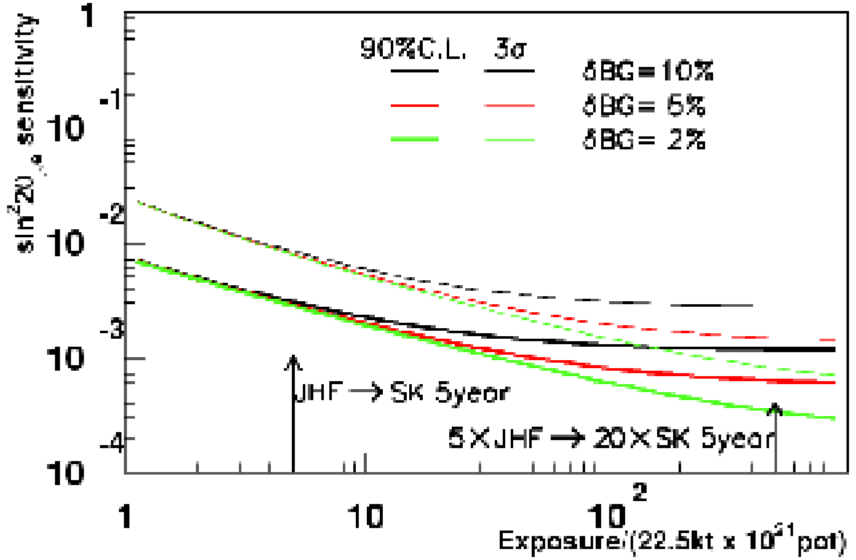
$\Rightarrow$ whatever the value of θ_{13} we need:

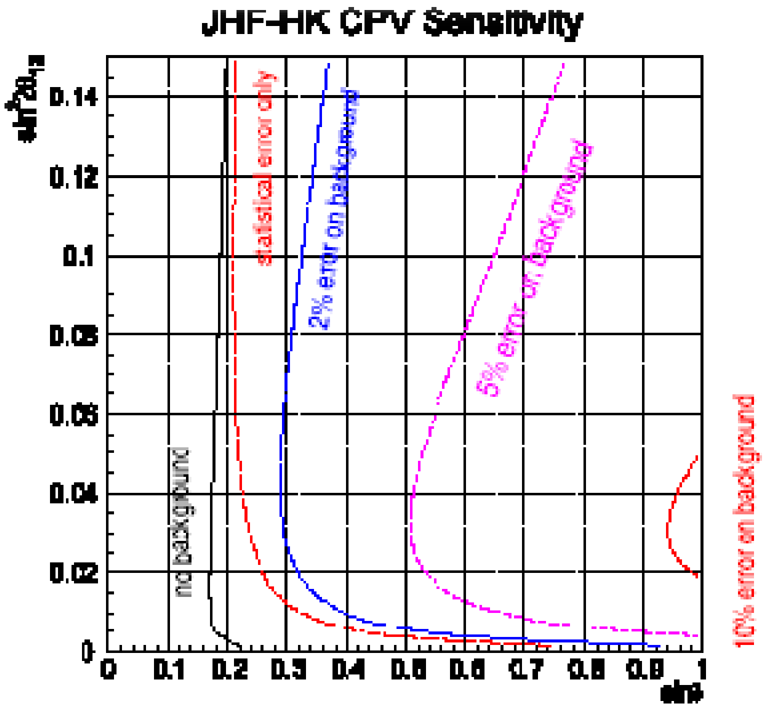
- More intense ν beams $\Rightarrow$ higher proton power (higher stats.)
- Bigger detectors: from kton to 100's x kton (higher stats.)
- Better background rejection (lower syst.)

Upgrades to T2K and NoνA

- **T2K** (from 2015+)
  - 0.75MW to 4MW upgrade to JPARC proton beam*
  - 50kton (SuperK) to 500kton (HyperK)
- **NoνA** (from 2015+)
  - 0.25MW to 2MW Proton Driver upgrade to NuMI beam*
  - Second detector sitting further off axis i.e. lower E_{ν_μ}, accessing second prob. maximum

* target technology must move on to withstand this intense p-beam!

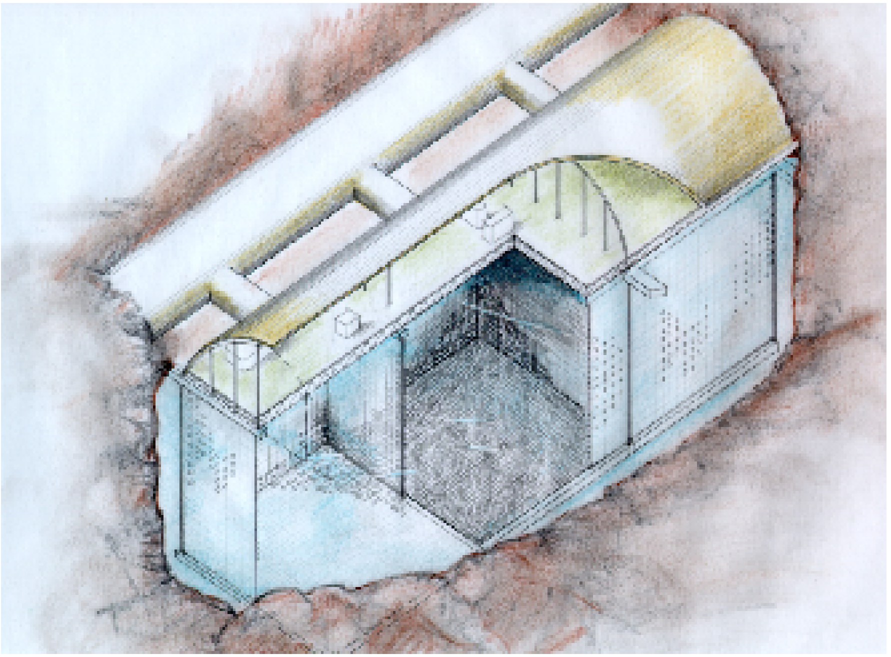




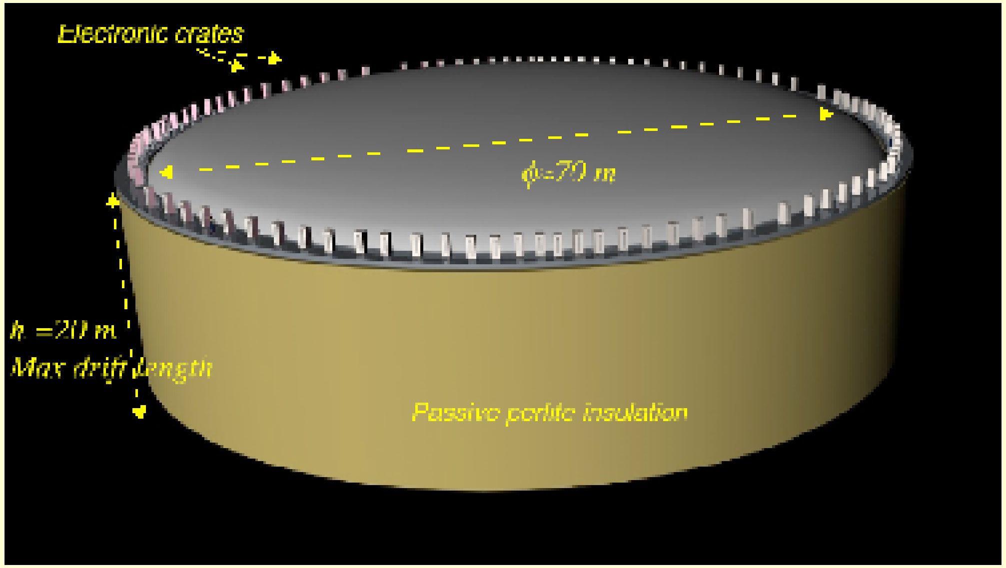
2 year neutrino run 7 year anti-neutrino run

Big Detectors

- UNO: water Cerenkov, 650kton (500kT fid. mass)
- 100 kton LiAr detector from the makers of ICARUS T600
- Independent physics program: proton decay limits improved by order of magnitude over SuperK, dark matter seraches, ...
- Costing upwards of $500M depending on degree of civil engineering

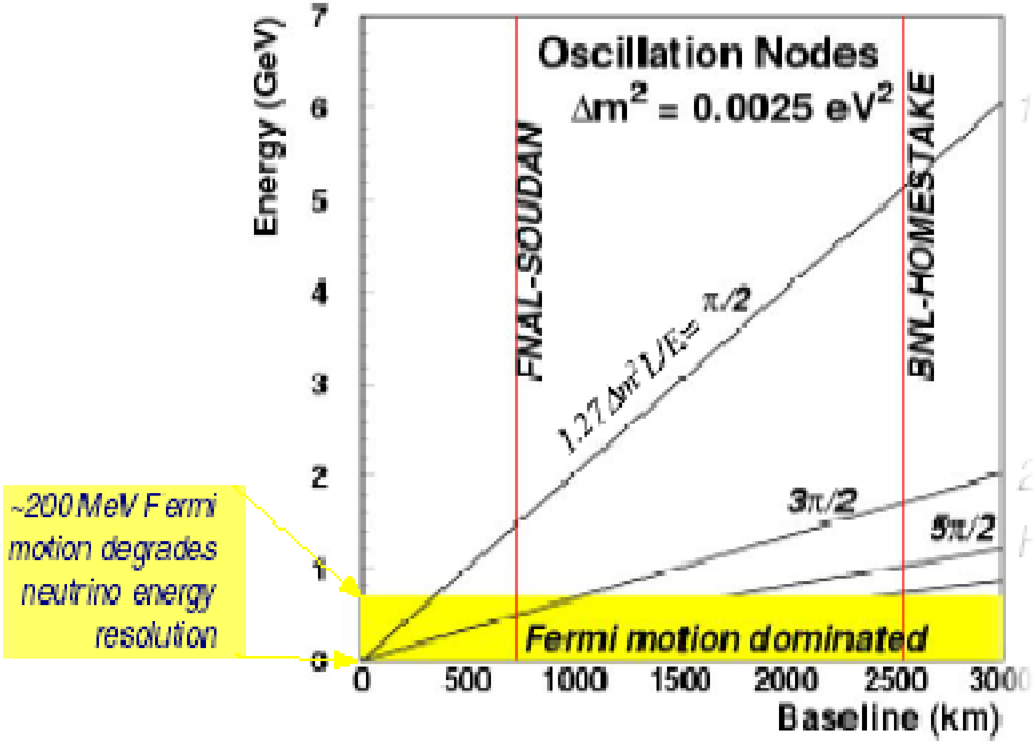


A 100 kton liquid Argon TPC detector



Next Generation of Superbeam LBL Experiments

- Given MW proton sources/Mton neutrino detectors, proposals for the next generation of experiment starting to appear (BNL→Homestake, FNAL→Homestake, CERN→Frejus, Tokai→Korea, ...)
- Physics case for broad-band beam and longer baselines strong:
  - Long baseline gives access to 2nd(and higher) maxima
  - Matter effects increase with L
  - Large CP effect ($\propto L$) compensates drop in statistics ($\propto 1/L^2$)

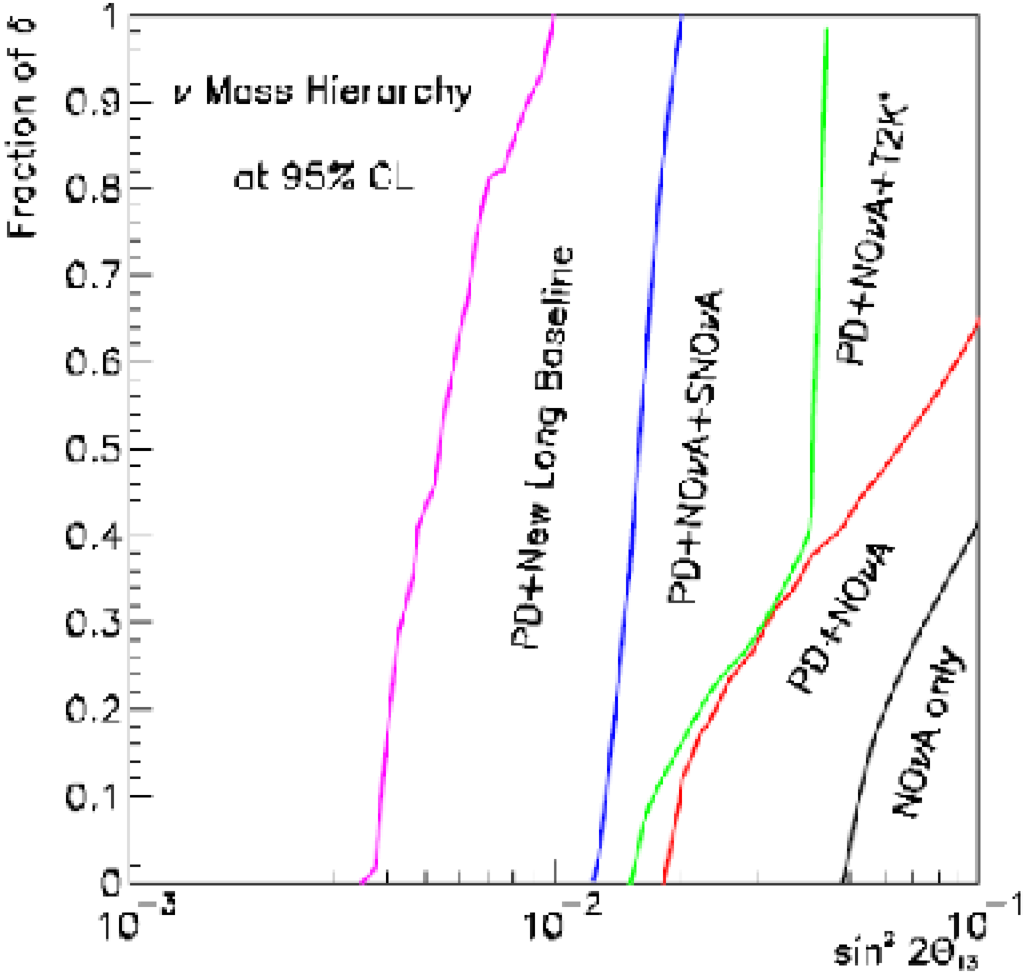


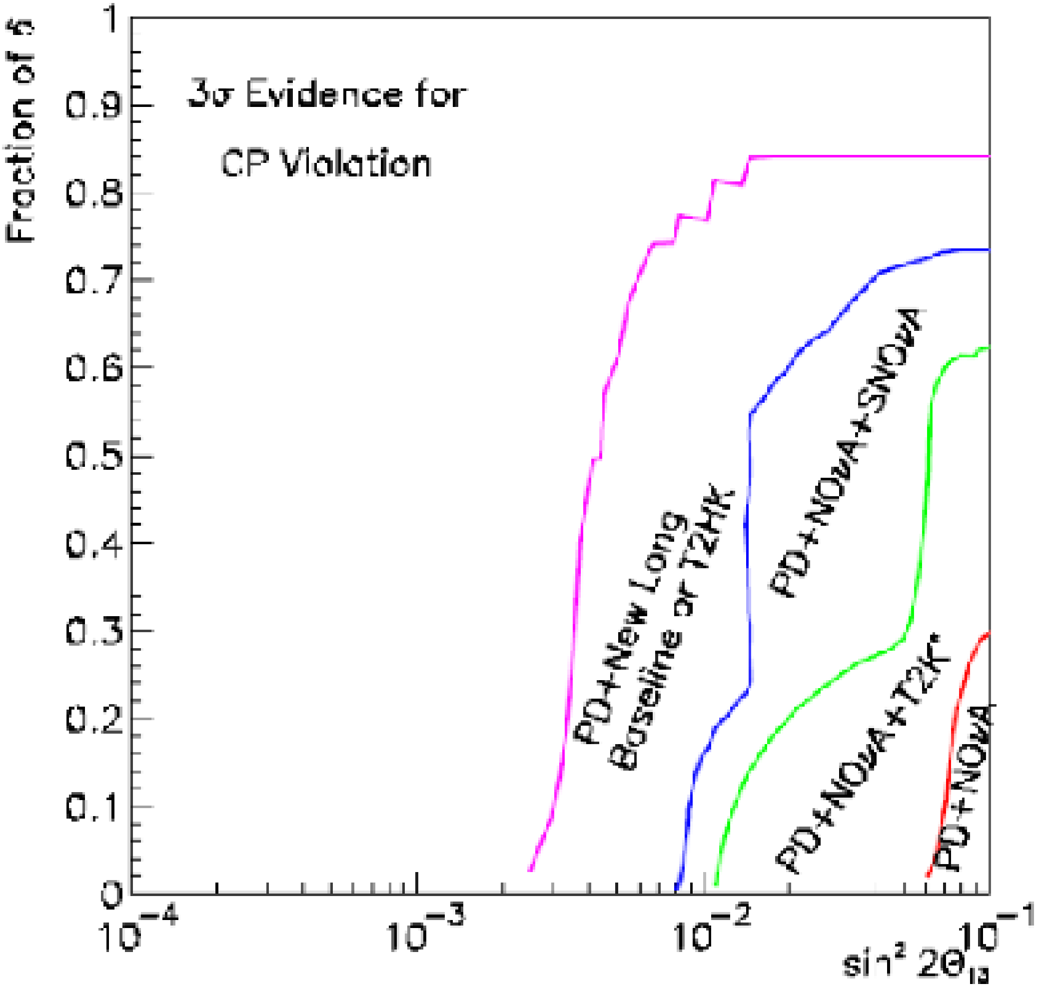
(Messler, NuFact05)

- All maxima sensitve to θ_{13},
- 1st maxima sensitive to mass hierachy,
- 2nd max. has larger CP asymmetry,
- higher max. are even sensitve to solar oscillations

Possible Physics Gains

e.g. the FNAL → Homestake proposal based on 4MW proton power and $L = 1290$km





Brice/Harris/Winter FNAL proton driver review, Dec. 2004

Limitations of Conventional Neutrino Beams

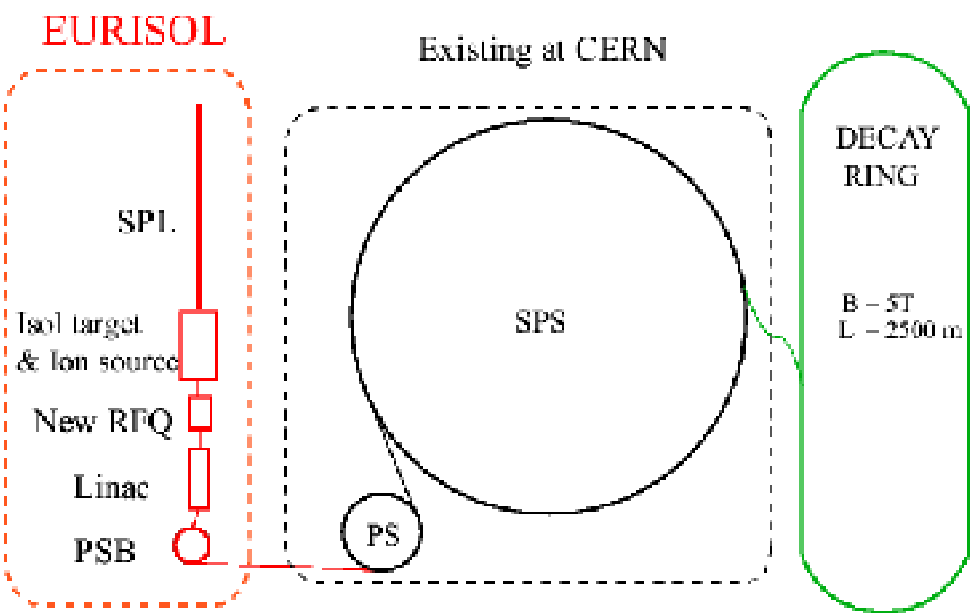
- Hard to predict the neutrino flux because of poorly known π, K production cross sections in the target material
- Contamination of the main flavour component ν_μ by $(\bar{\nu}_\mu, \nu_e, \bar{\nu}_e)$ from 'wrong-sign' pions, kaons and muon decays
- Poor control over beam energy

Solution: Accelerate the Parent Particles!

Collect, focus and accelerate the neutrino parents (impossible for short-lived pions): muons (Neutrino Factory) or ^{6}He, ^{18}Ne (Beta Beam).

Big Advantages:

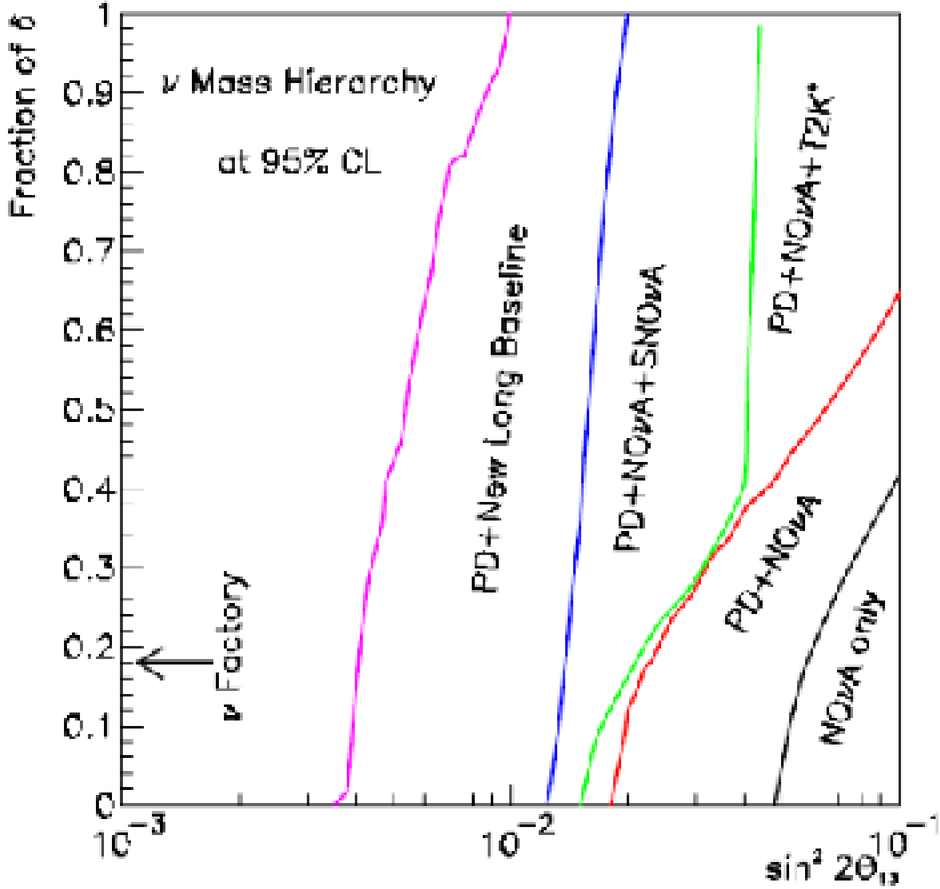
- Flavour content and energy spectrum of beam depend only on well-known properties of decaying state
- Flux normalisation given by luminosity of parent beam

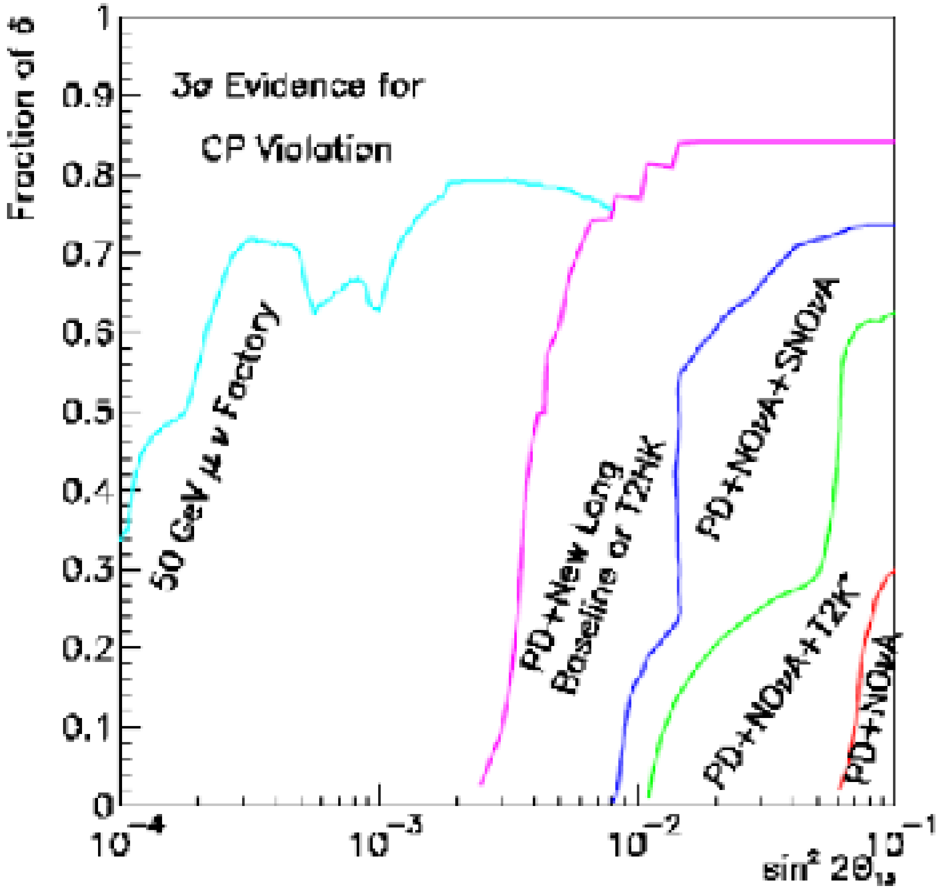


- 4MW 2.2GeV CERN Superconducting Proton Linac (SPL)
- Low energy, wide-band ($\langle E_\nu \rangle \sim 0.3$GeV)
- Far detector in Frejus tunnel, $L = 130$km
- Large water Čerenkov (UNO-like) or LiAr TPC
- Much existing infrastructure (SPS, ISOLDE) + SPL can be used first (~2015) to supply a CERN-Frejus Superbeam expt.

Possible Physics Gains

Beta-beam/Neutrino Factory Represents state-of-the-art in oscillation experiment design and our best chance of measuring CP violation in the lepton sector





Brice/Harris/Winter FNAL proton driver review, Dec. 2004

Summary/Conclusion

Future path for accelerator experiments seems well defined (given funding!):

- Near-future ($0-5$ years):
  - MINOS: $\Delta m^2_{23}, \sin^2 2\theta_{23}$ to 10%
  - OPERA+ICARUS: observe ν_τ appearance
  - MINOS+OPERA+ICARUS: push limits on θ_{13}
- Mid-term ($5-10$ years):
  - NoνA+T2K: $\Delta m^2_{23}, \sin^2 2\theta_{23}$ to $\sim 2\%$, establish non-zero θ_{13} (with reactor results), begin exploring mass hierachy and CPV
- Long-term($15-20+$ years):
  - Next generation Superbeams: $\Delta m^2_{23}, \sin^2 2\theta_{23}$ to $\sim 1\%$, θ_{13} to few$\%$, determine mass hierachy and search for CPV (if $\sin^2 2\theta_{13} >\sim 0.01$)
  - Beta-beam and neutrino factories: precisely fix all params. and offer best chance to measure CPV

Caveat: Some priorities may change e.g. if LSND result is verifed by MiniBooNE