Future precision neutrino-oscillation experiments

Vulcano Workshop
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Neutrino mixing and oscillations: where do we stand ?

Our knowledge about neutrino masses and mixing

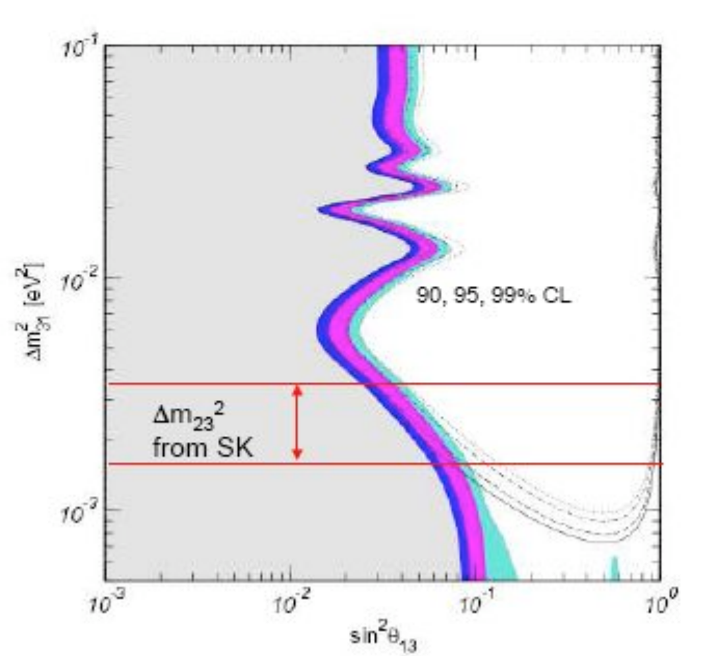
- there exist 3 'light' neutrinos (LEP): $N\nu = 2.984 \pm 0.008$
- limits from direct mass measurements are small (tritium & cosmology):
  WMAP: $\Sigma_i\, m_i < 0.7$ eV (95% CL)
- solar and atmospheric neutrino deficit: neutrinos mix (oscillations) →
  they are massive: m (heaviest ν) $> \sim 0.05$ eV
  PMNS matrix (3 x 3)
- oscillation parameters: 2 large mixing angles $\theta_{sol} \sim \theta_{12}$, $\theta_{atm} \sim \theta_{23}$
  2 independent mass splittings: $\Delta m^2_{sol} \sim \Delta m^2_{12}$
  (masses are small, indeed) $\Delta m^2_{atm} \sim \Delta m^2_{23}$

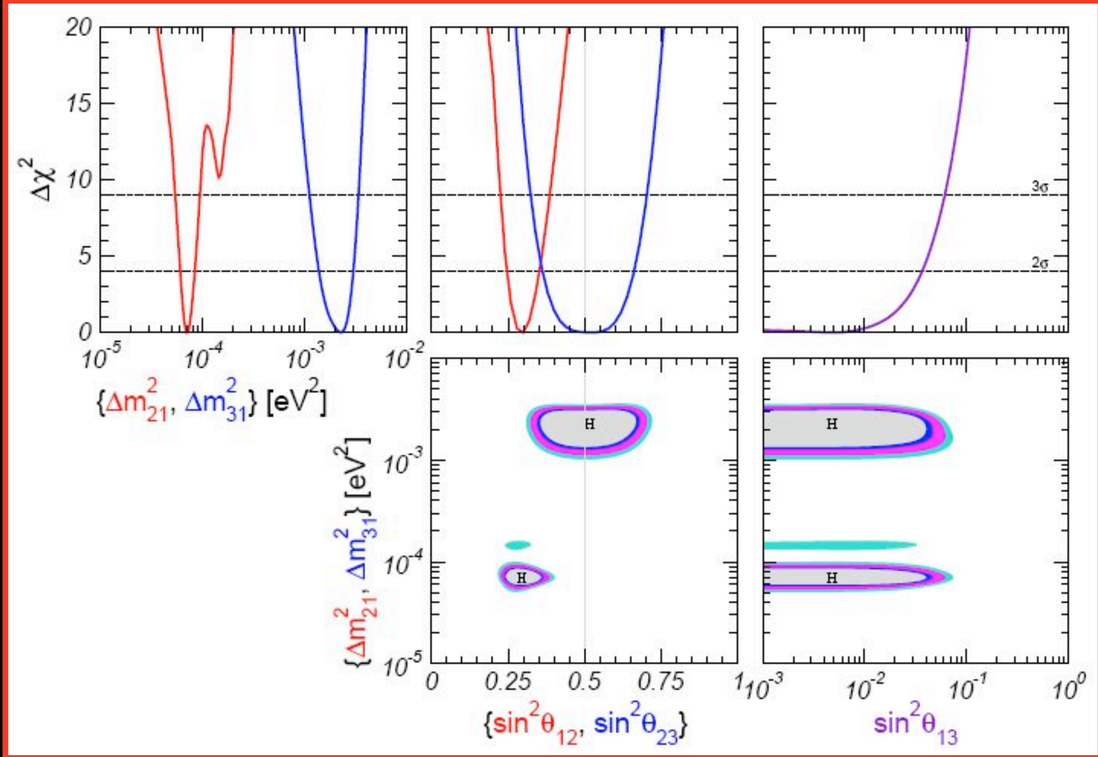
What we do not know…

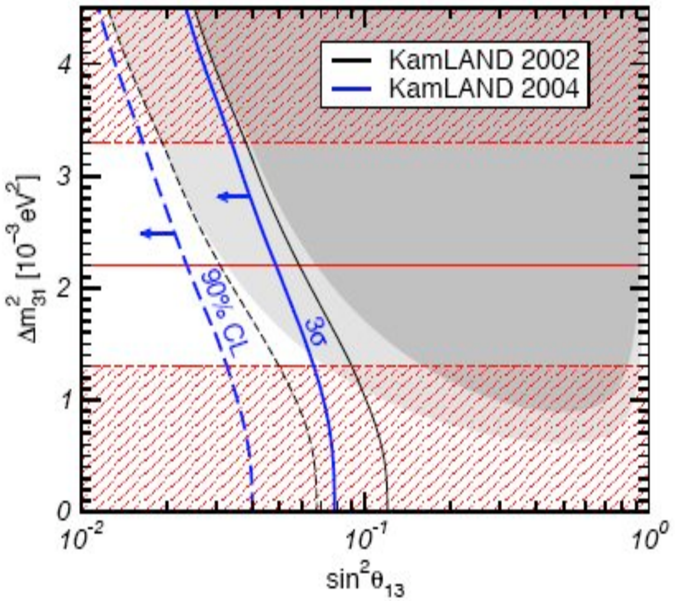
- absolute mass values (and why are they small ?)
- why θ_{12} and θ_{23} angles are large and θ_{13} seems very small or null ?
- is mass hierarchy the same as for charged leptons (sign of Δm^2_{23})
- is there any CP violating phase in the mixing matrix ?

LSND effect ? Wait for MiniBoone…

Our knowledge of the oscillation parameters. Global fits from Maltoni et al. 03, Valle 05, Fogli et al. 06 (all data included, except the very recent MINOS data)







$$\sin^2\theta_{13} = 0.9^{+2.3}_{-0.9} \times 10^{-2}$$

$$\Delta m^2_{12} = 7.92(1 \pm 0.09) \times 10^{-5}\ \mathrm{eV}^2,$$

$$\sin^2\theta_{12} = 0.314(1^{+0.18}_{-0.18}),$$

$$\Delta m^2_{23} = 2.4(1^{+0.21}_{-0.26}) \times 10^{-3}\ \mathrm{eV}^2,$$

$$\sin^2\theta_{23} = 0.44(1^{+0.41}_{-0.22}),$$

$\sin^2\theta_{13} < 0.04 \rightarrow \sin^2 2\theta_{13} < 0.15$ and $\theta_{13} < 11°$

Goals of planned and future neutrino beam experiments:

- observe ν_τ appearance → …find the body after the murder…
- is there (some) room for a sterile neutrino? → MiniBoone and ν_μ disappearance
- measure L/E dependence → atmospheric and WBB experiments (fixed L)
- accurately measure the two Δm^2 , θ_{12} and θ_{23} → is θ_{23} exactly $\pi/4$?
- find the value of θ_{13} from P(ν_μ-ν_e) → key measurement
- show MSW matter effects (without CP violation effects) → mass hierarchy
- show CP violating effects (without matter effects) → the ultimate goal ?
- …be ready for the unexpected ! → experiments may be running for long time…

this talk: focus on accelerator experiments

Neutrino mixing matrix and general 3 neutrino oscillation probability

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2}\,\nu_1 \\ e^{i\alpha_2/2}\,\nu_2 \\ \nu_3 \end{pmatrix}$$

$$P(\nu_\ell \to \nu_{\ell'}) = |\sum_i U_{\ell i} U^*_{\ell' i} e^{-i(m_i^2/2E)L}|^2$$

$$= \sum_i |U_{\ell i} U^*_{\ell' i}|^2 + \Re \sum_i \sum_{j \neq i} U_{\ell i} U^*_{\ell' i} U^*_{\ell j} U_{\ell' j} e^{i\frac{|m_i^2 - m_j^2| L}{2E}}$$

The formula simplifies under the empirical assumptions that:

- $\Delta m^2_{atm} >> \Delta m^2_{sol}$
- L is comparable to the atmospheric oscillation length (~ 1000 km)
- the angle θ_{13} is small

For the special case of $\nu_\mu \rightarrow \nu_e$ oscillations, we have:

$$P(\nu_\mu \rightarrow \nu_e) = \Sigma_{i=1,4} P_i$$

$$P_1 = \sin^2\theta_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2 \frac{B_\pm L}{2} \quad \text{atmospheric part}$$

$$P_2 = \cos^2\theta_{23} \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2 \frac{AL}{2} \quad \text{solar part}$$

$$P_3 = J \cos\delta \left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right) \cos\frac{\Delta_{13}L}{2} \sin\frac{AL}{2} \sin\frac{B_\pm L}{2} \quad \text{interference}$$

$$P_4 = \mp J \sin\delta \left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right) \sin\frac{\Delta_{13}L}{2} \sin\frac{AL}{2} \sin\frac{B_\pm L}{2} \quad \text{interference}$$

θ_{13} is the link between solar and atmospheric oscillations

where

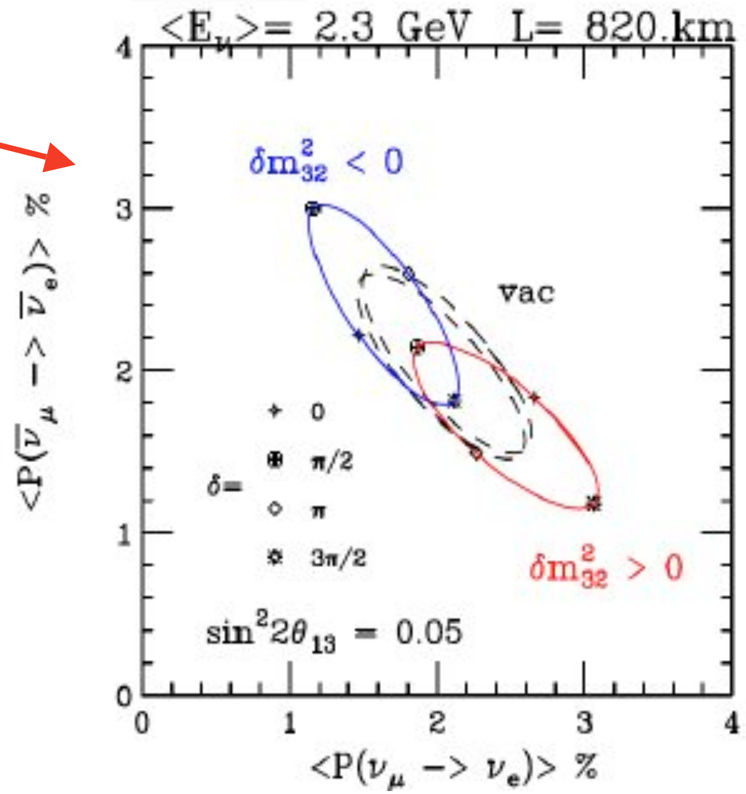
$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$

$$A = \sqrt{2} G_F n_e$$

$$B_\pm = |A \pm \Delta_{13}|$$

$$J = \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

and the $\pm$ signifies neutrinos or antineutrinos



In vacuum, at leading order:

$$P(\nu_\mu \rightarrow \nu_e) \propto \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2 \frac{\Delta m^2_{23} L}{4E}$$

Work just done or in progress…

K2K: the mother of all LBL experiments

see Y. Obayashi's talk

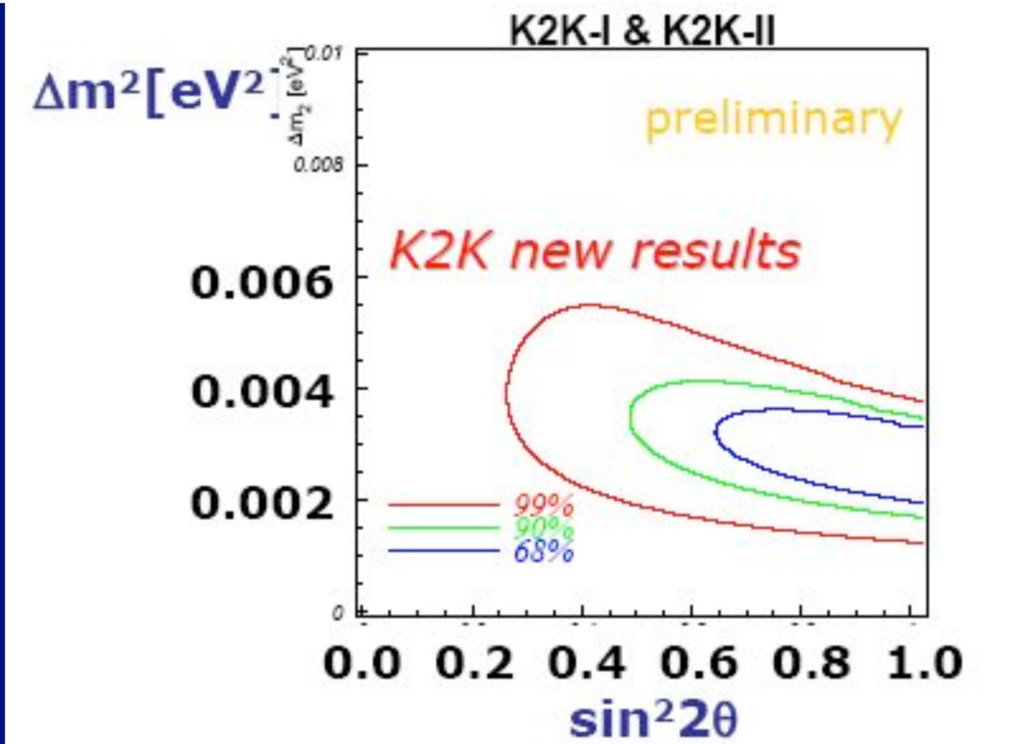
Super-K
(far detector)
50 kton Water Cherenkov det.

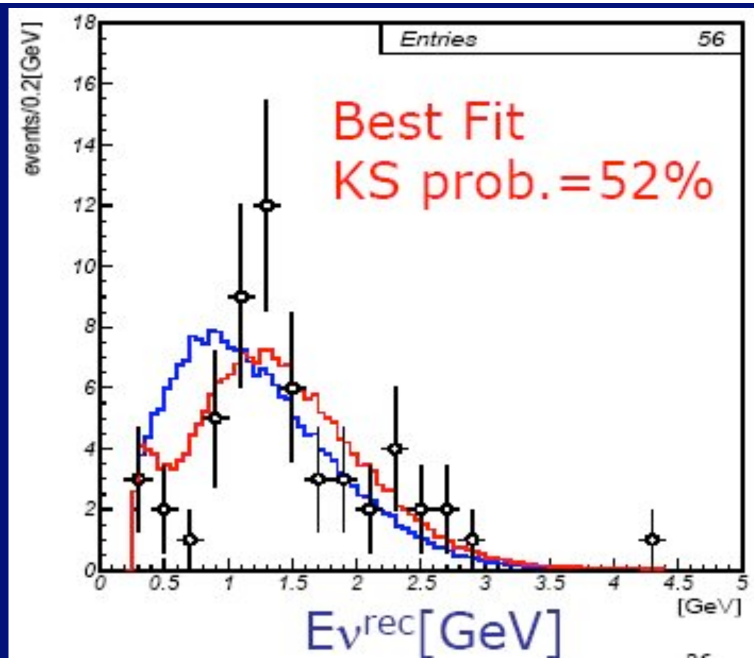
12GeV PS@KEK
- **ν beam line**
- **Beam monitor**
- **Near detectors**

ν_μ disappearance experiment to probe the SK atmospheric neutrino result.

Analogous case to Kamland vs solar neutrino experiments

near/far detectors comparison: event rate and energy spectrum shape





K2K results:

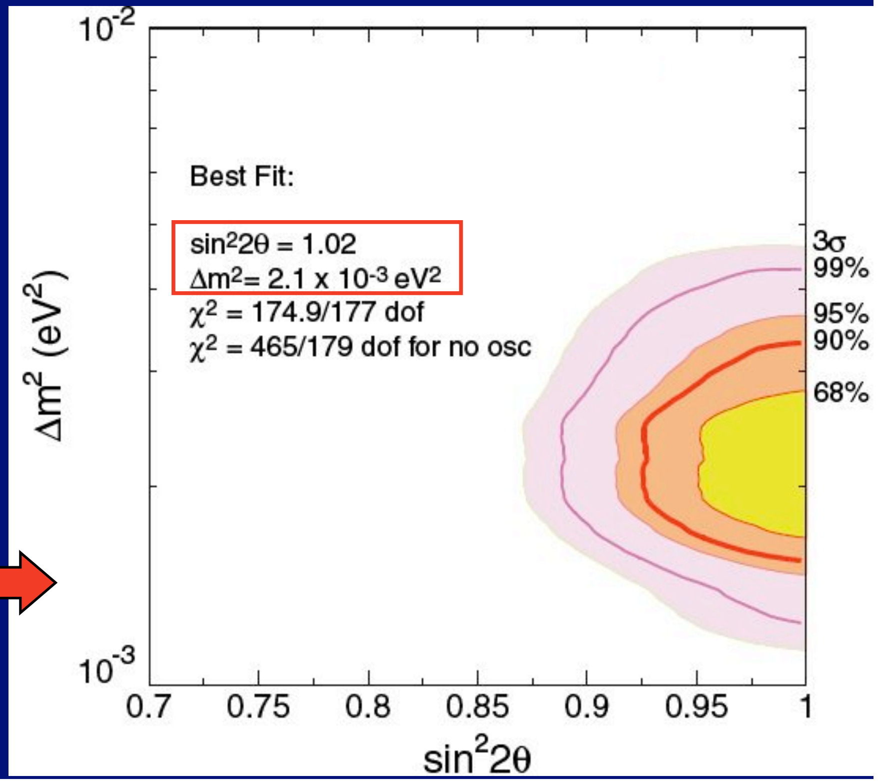
$1.7 < \Delta m^2 < 3.5\ eV^2$ for $\sin^2 2\theta = 1$ (90% CL)

(ν_μ disappearance plus shape distortion)

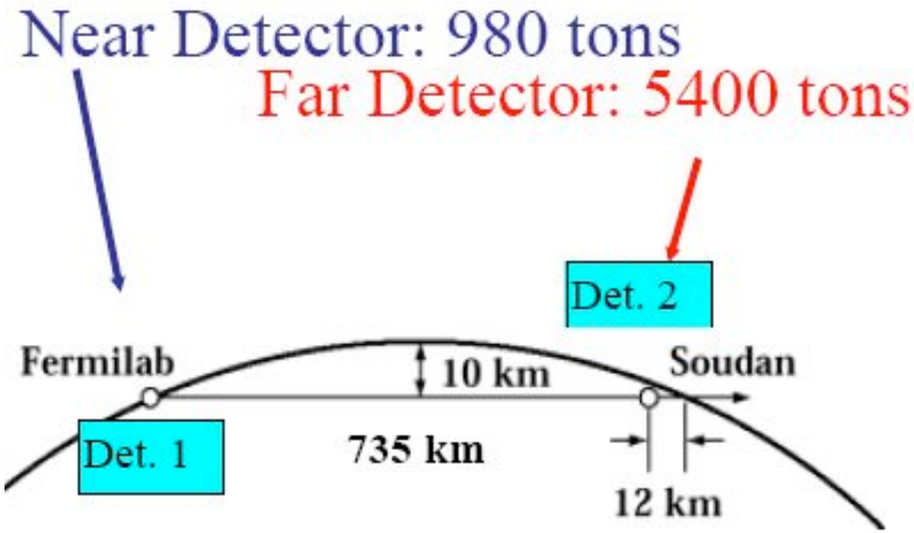
oscillation hypothesis confirmed at $3.9\ \sigma$

K2K confirms SK:

$1.5 < \Delta m^2 < 3.4\ eV^2$ for $\sin^2 2\theta > 0.93$ (90% CL)



Fresh results from MINOS in the NuMi neutrino beam



Magnetized steel/scintillator calorimeter

- low E neutrinos (few GeV): ν_μ disappearance experiment
- 4 x10^{20} pot/year → 2500 ν_μ CC/year
- compare Det1-Det2 response vs E → in 2-6 years sensitivity to Δm^2_{atm}
- main goal: reduce the errors on Δm^2_{23} and $\sin^2 2\theta_{23}$ as needed for $\sin^2 2\theta_{13}$ measurement

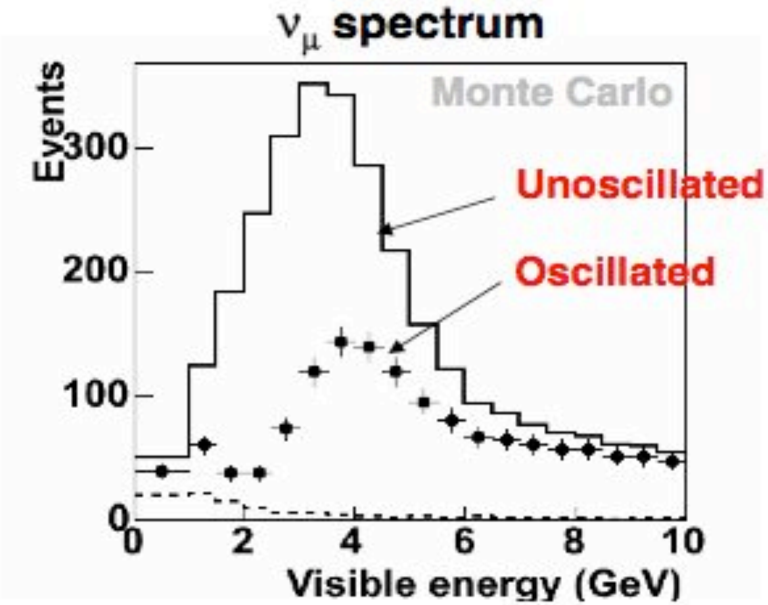
1 kton MINOS near detector (Fermilab)

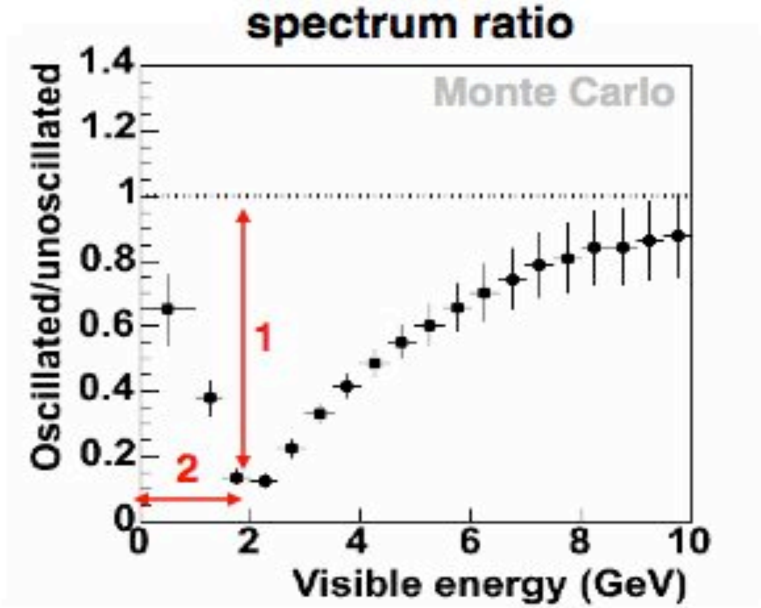
5.4 kton MINOS far detector (Soudan Mine)

Example of a ν_μ disappearance measurement

- Look for a deficit of ν_μ events at Soudan…

$$P(\nu_\mu \to \nu_\mu) = 1 - \underbrace{\boxed{\sin^2 2\theta}}_{1} \sin^2(1.267 \underbrace{\boxed{\Delta m^2}}_{2} L/E)$$

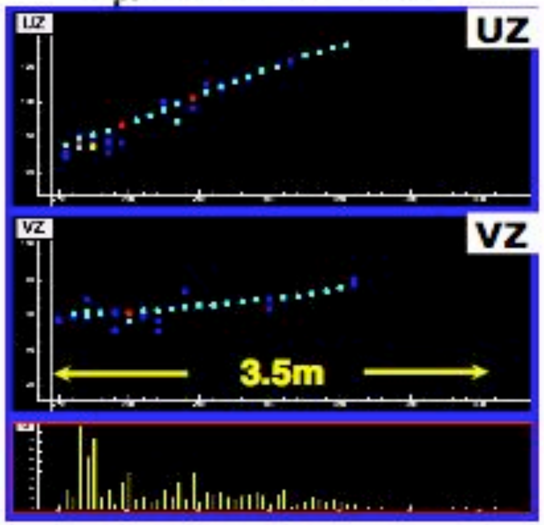




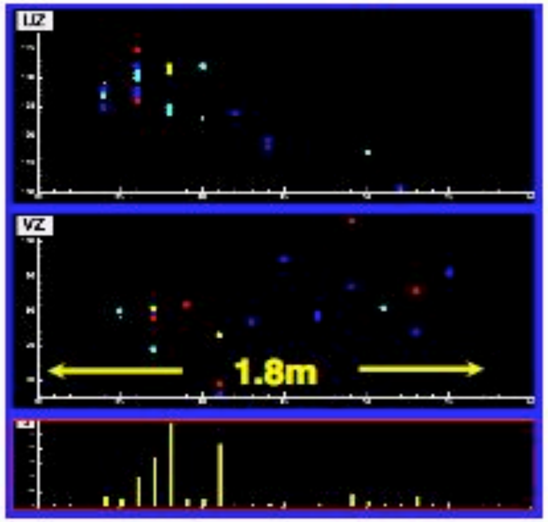
Event topologies

Monte Carlo

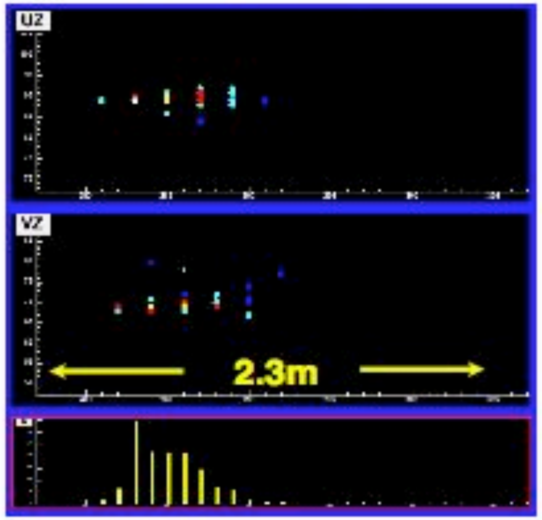
ν_μ CC Event



NC Event



ν_e CC Event



- long μ track+ hadronic activity at vertex
- short event, often diffuse
- short, with typical EM shower profile

$$E_\nu = E_{shower} + P_\mu$$

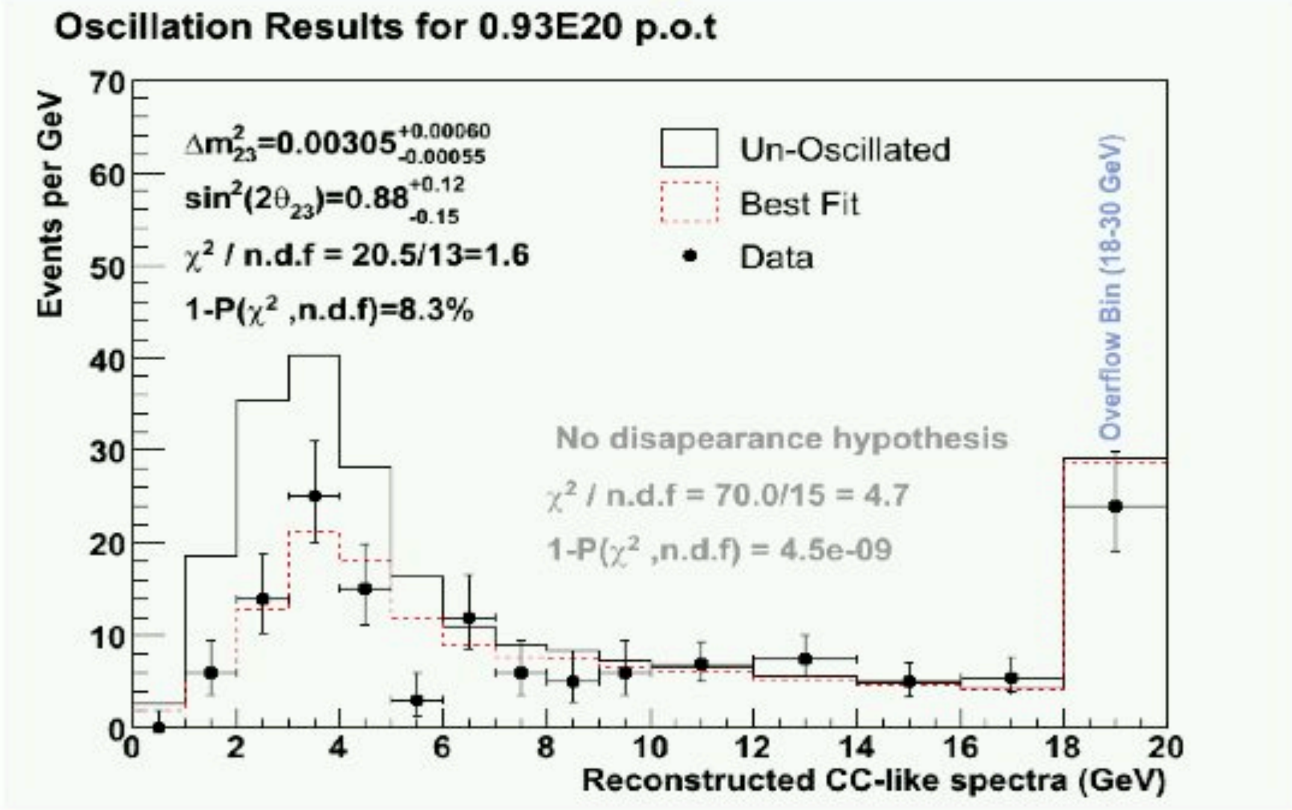
$55\%/\sqrt{E}$ 6% range, 10% curvature

Numbers of observed and expected events

Data sample	observed	expected	ratio	significance
All CC-like events ($\nu_\mu+\bar{\nu}_\mu$)	204	298±15	0.69	4.1σ
ν_μ only (<30 GeV)	166	249±14	0.67	4.0σ
ν_μ only (<10 GeV)	92	177±11	0.52	5.0σ

- We observe a 33% deficit of events between 0 and 30 GeV with respect to the no oscillation expectation.
  - Numbers are consistent for $\nu_\mu+\bar{\nu}_\mu$ sample and for the ν_μ-only sample
- **The statistical significance of this effect is 5 standard deviations**

Best-fit spectrum



$$\chi^2(\Delta m^2, \sin^2 2\theta) = \sum_{i=1}^{nbins} 2(e_i - o_i) + 2o_i \ln(o_i / e_i)$$

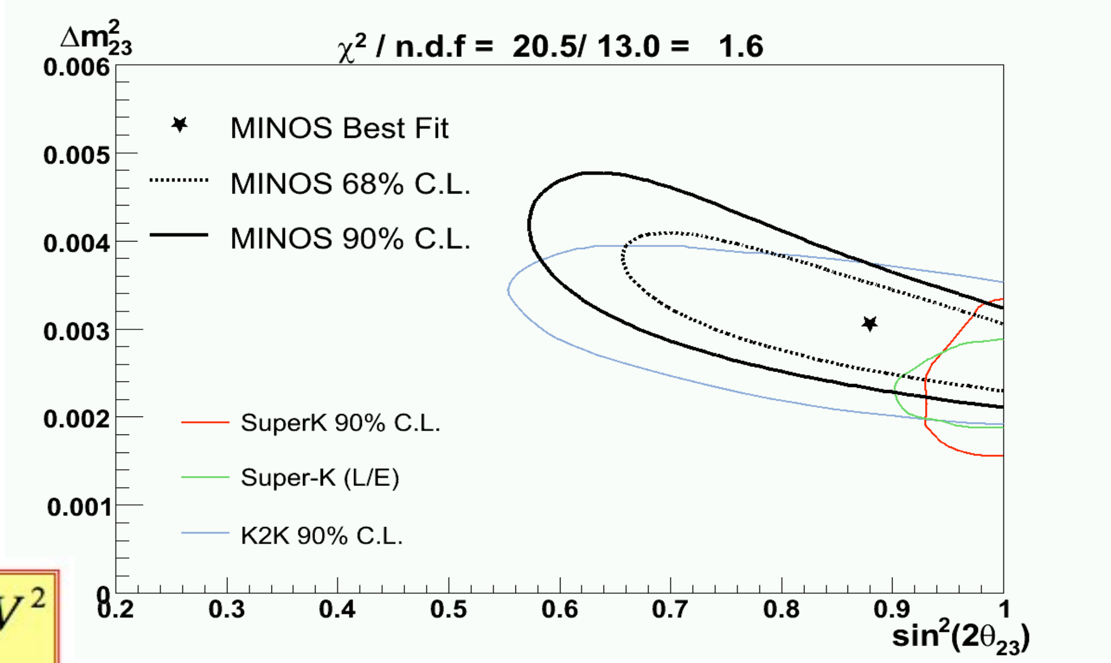
- Measurement errors are 1 sigma, 1 d.o.f.

Results

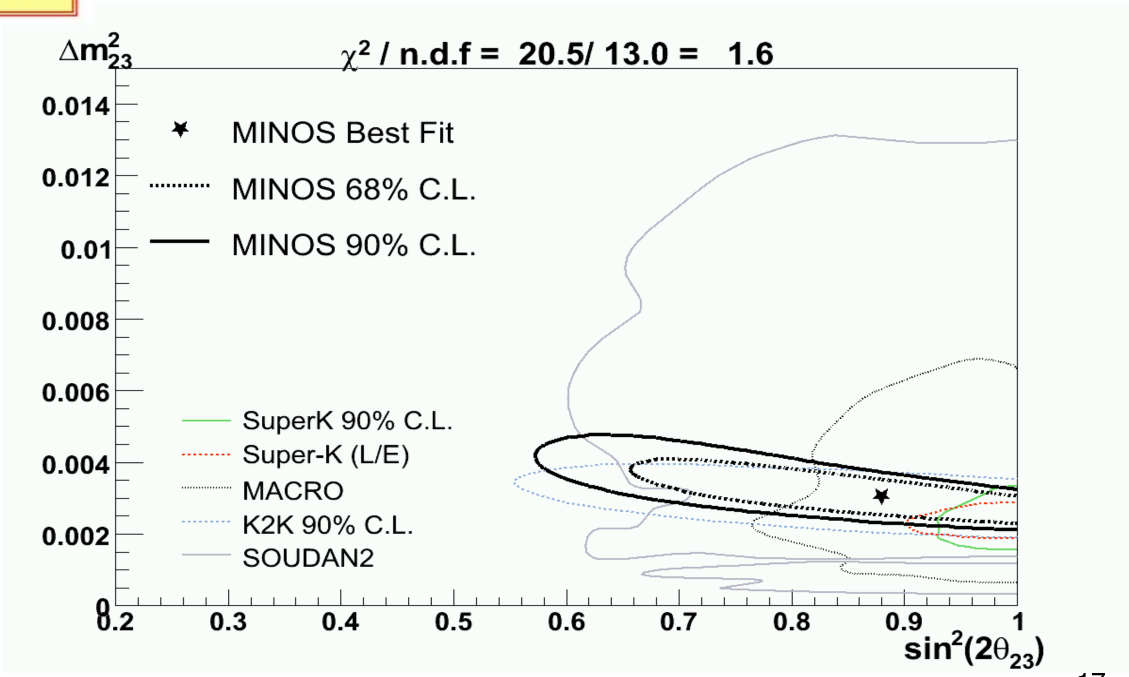
0.93 x 10^{20} p.o.t.

$$\Delta m^2_{23} = 3.05^{+0.60}_{-0.55}(stat) \pm 0.12(syst) \times 10^{-3}\,eV^2$$

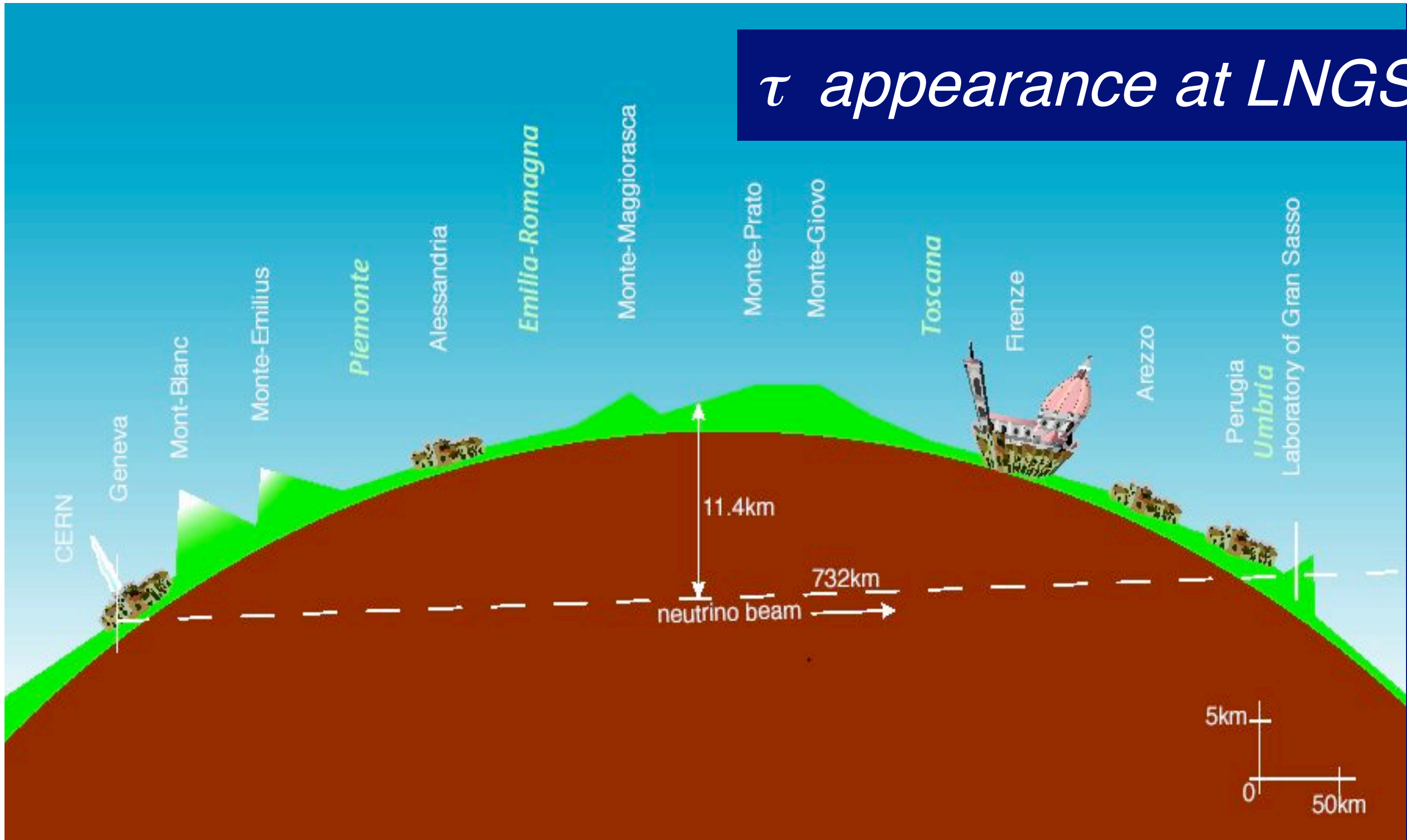
$$\sin^2 2\theta_{23} = 0.88^{+0.12}_{-0.15}(stat) \pm 0.06(syst)$$



Another confirmation of the SK result obtained with atmospheric neutrinos



τ appearance at LNGS in the CNGS beam



Start 2006

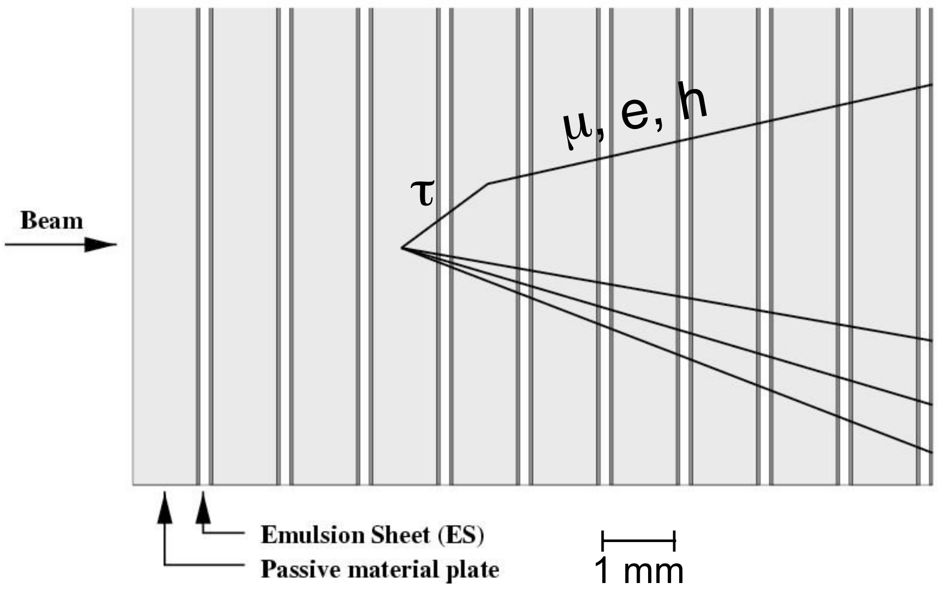
- High energy beam: <E> ~17 GeV: τ appearance search
- 4.5 x10^{19} pot/year from the CNGS. In the hypothesis of no oscillation:
- 2600 ν_μ CC/year per kton detector mass
- Assuming ν_μ - ν_τ oscillation, with parameters $\sin^2 2\theta = 1$ and $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2:

  15 ν_τ CC interactions /year per kton
- CNGS beam ready to be commissioned
- A dedicated experiment at LNGS: OPERA

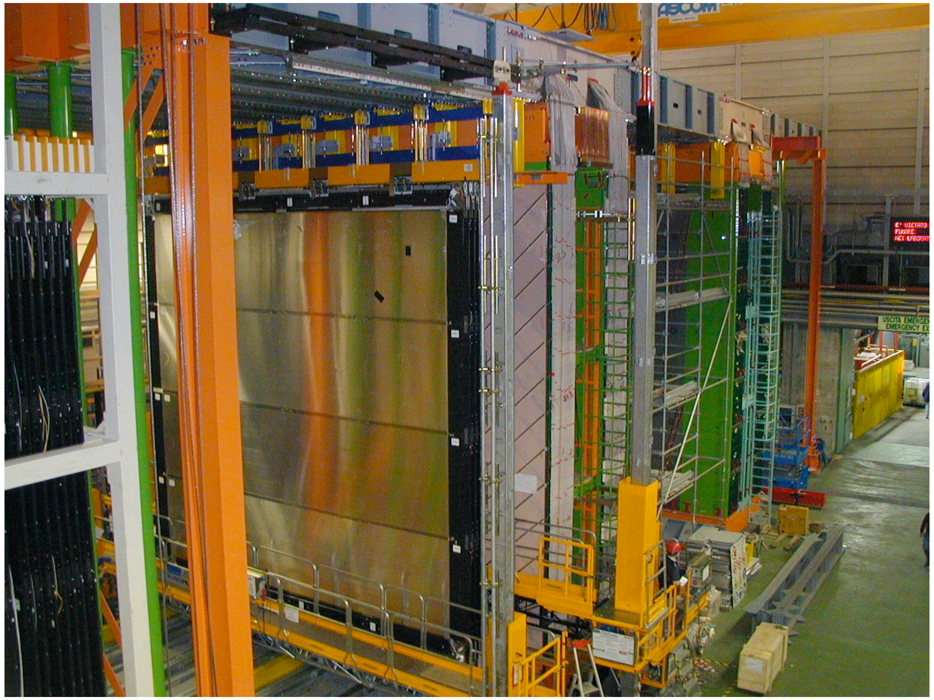
The OPERA experiment at LNGS: the rebirth of the emulsion technique

see G.Giacomelli's talk

- detector: 1800 ton emulsion/lead bricks (ECC technique) complemented by tracking scintillator planes and two muon spectrometers
- industrial emulsion production and handling
- need huge scanning power/speed: > tens of automatic microscope running in parallel @ 20 cm^2/hour (advances of the technique)

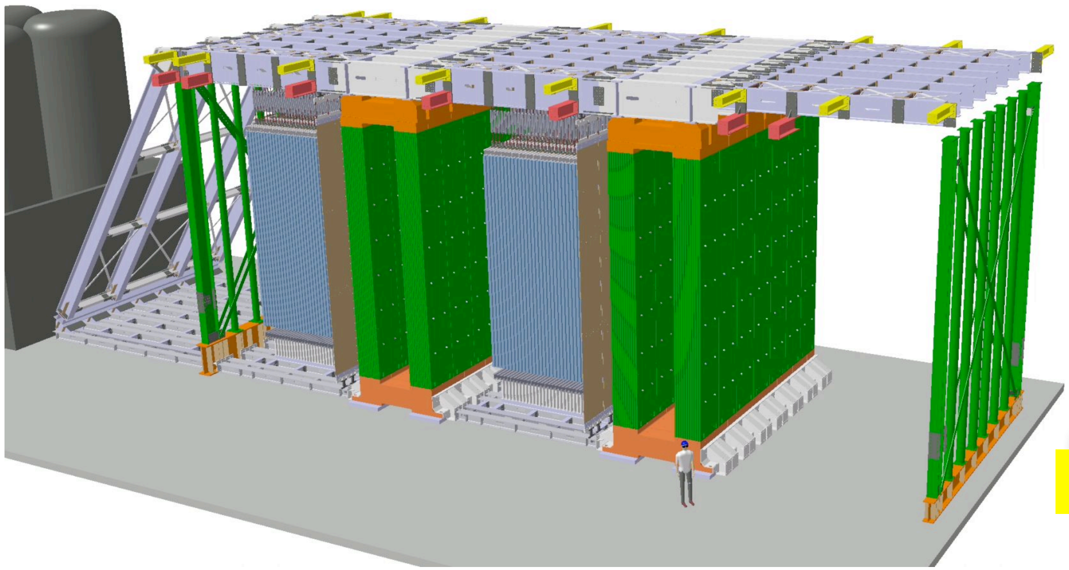


- specialized, single task experiment
- low BG: <1 event (τ track reconstruction)
- low statistics: about 10 events/5 years at nominal CNGS intensity @ SK parameter values: statistics goes like $(\Delta m^2)^2$
- aim at beam intensity increase
- installation in progress: technical runs in 2006 with first ν events
- huge amount of work for infrastructure: film handling, brick construction, film scanning



The OPERA detector installation at the Gran Sasso Hall C

One of the automatic scanning microscopes equipped with a robot for emulsion-film feeding & replacement (Bern University)



Artistic view of the full detector

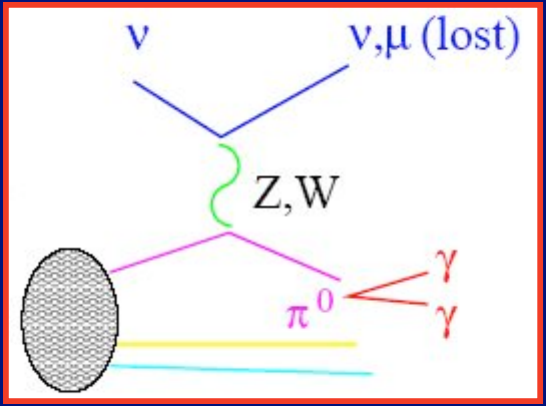
Measure θ_{13}

Simple considerations

$\nu_\mu \rightarrow \nu_e$ oscillation as a tool to measure θ_{13} with accelerator neutrino experiments.

Future 'Super-CHOOZ-like' reactor experiments are difficult (and not covered here).
Existing or planned atmospheric neutrino detectors can be limited by statistics.

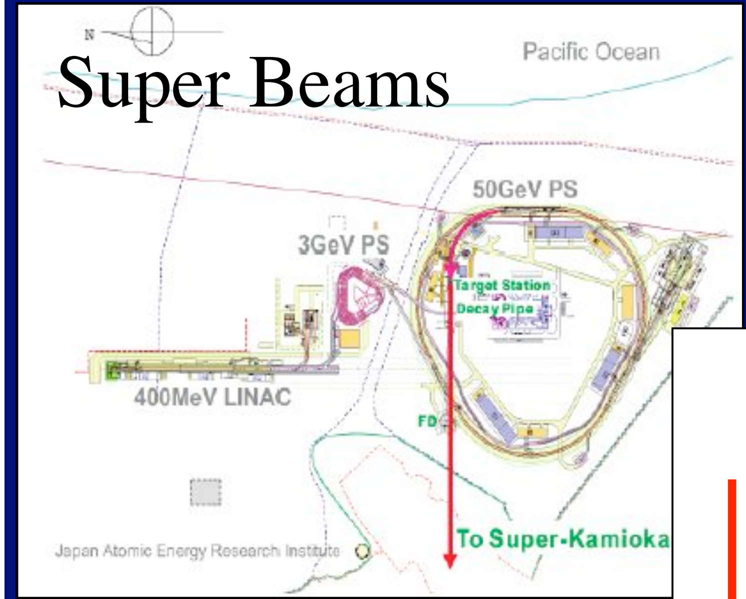
- small effect (< 5% from CHOOZ)
- prompt ν_e contamination at % level (accelerator neutrino beams)
- main BG: $\pi°$ production in NC and CC interactions
- additional BG: low energy muons and pions can fake electrons



$\nu_e \rightarrow \nu_\mu$ oscillations can solve most of the problems but hard to make ν_e beams (wait for a next generation facilities)

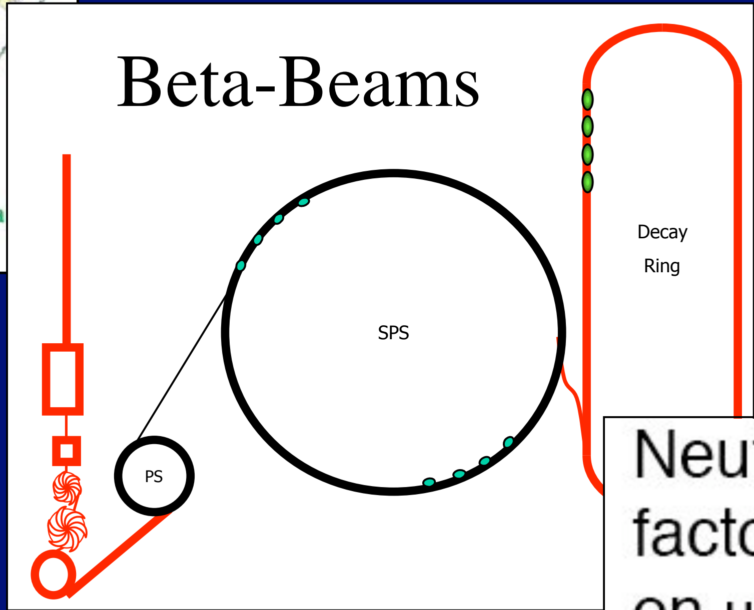
In any case high intensity is a must !

Need high intensity: future neutrino facilities



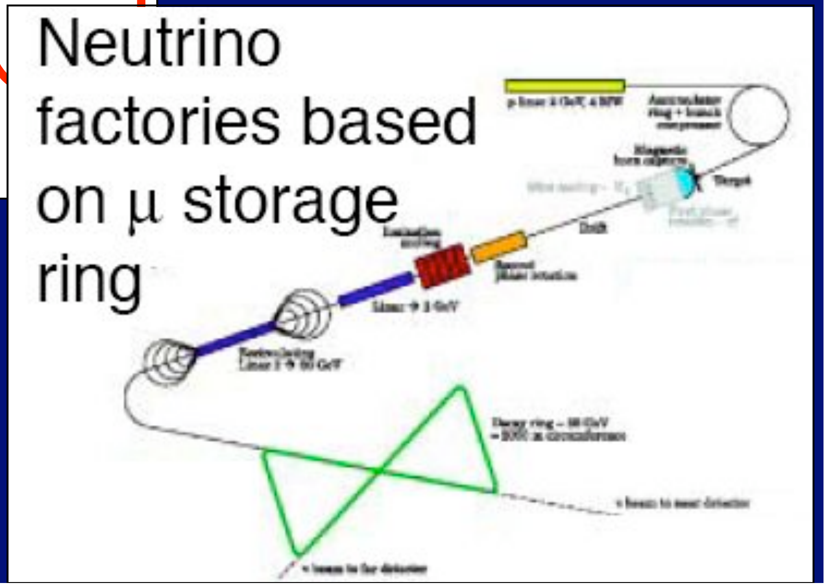
$$\pi^{\pm} \rightarrow \mu^{\pm}\, \overset{(-)}{\nu}_{\mu}$$

Select focusing sign



$${}^{Z}A \rightarrow {}^{Z\mp1}A\ \beta^{\pm}\ \overset{(-)}{\nu}_{e}$$

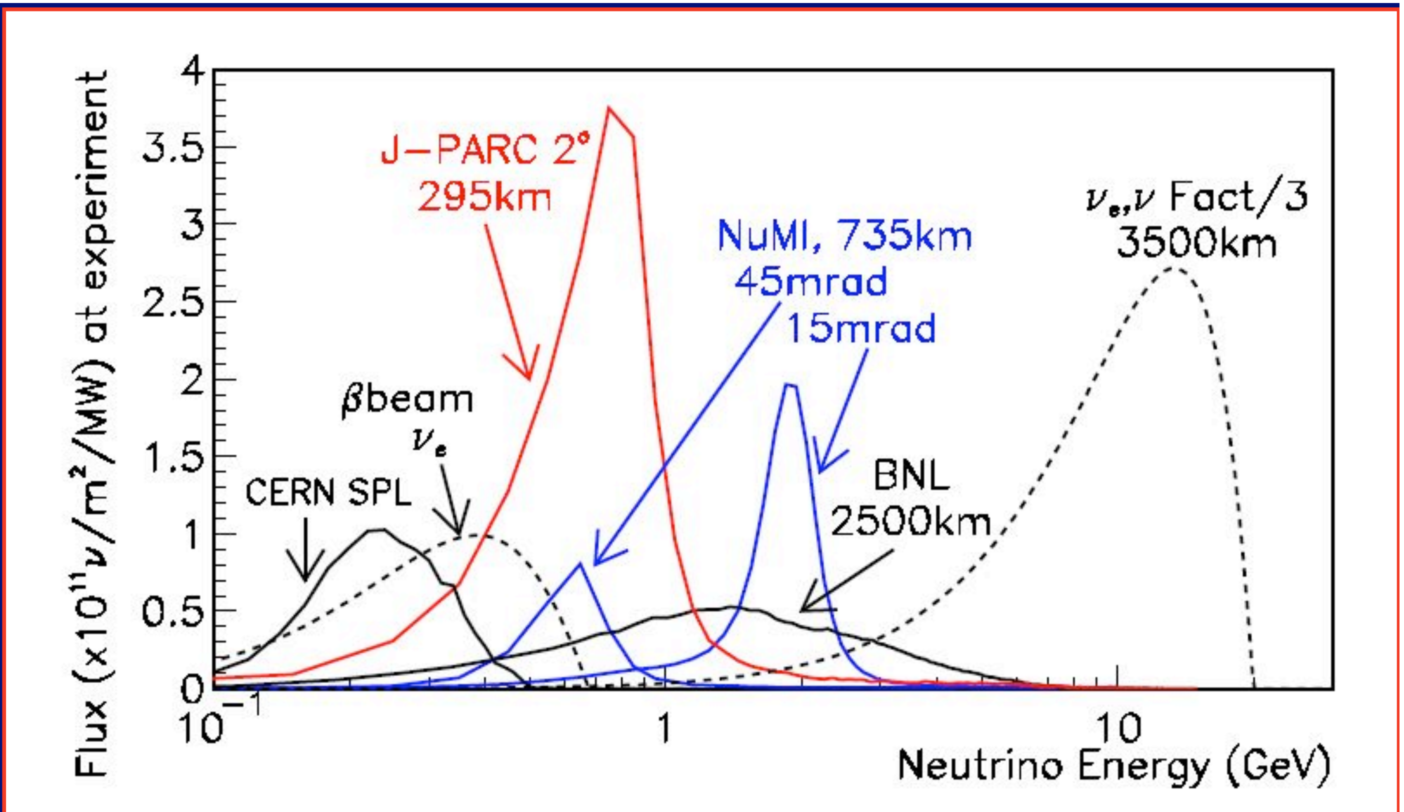
Select ion



$$\left.\begin{array}{l} \mu^{-} \rightarrow e^{-}\bar{\nu}_{e}\nu_{\mu} \\ \mu^{+} \rightarrow e^{+}\nu_{e}\bar{\nu}_{\mu} \end{array}\right\}$$

Select ring sign

Future neutrino beams

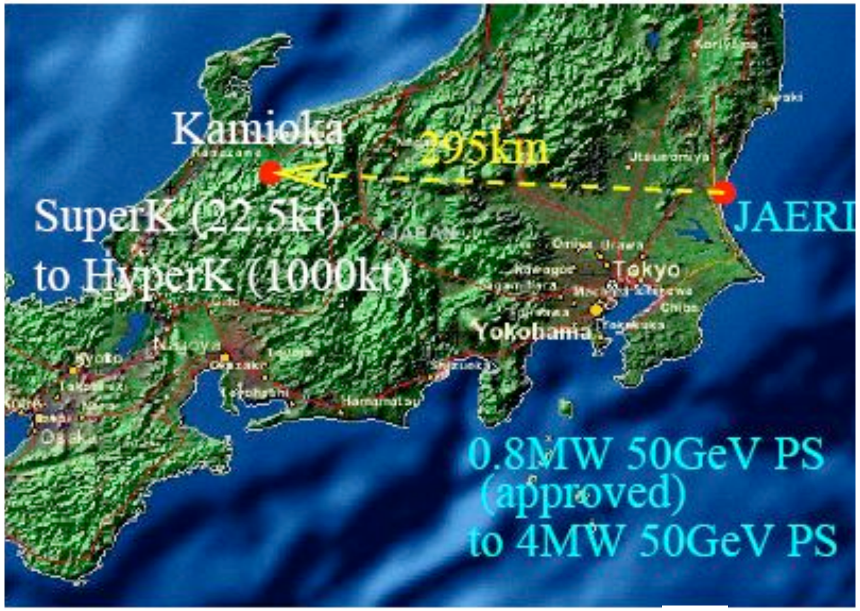


Outstanding goals

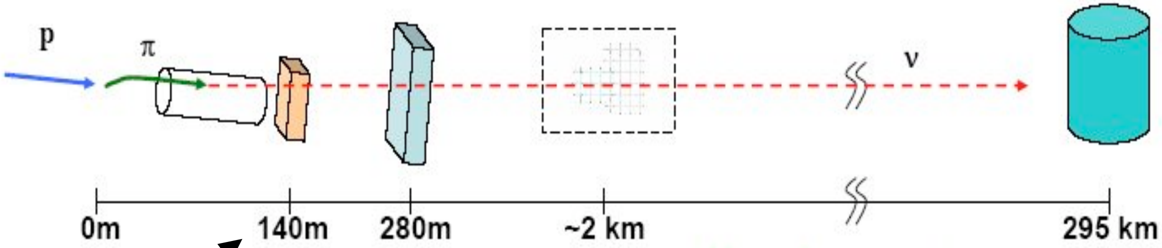
Physics	Value of $\sin^2 2\theta_{13}$ $> 4\times10^{-2}$	$> 1\times10^{-2}$	$> 10^{-3}$	$> 10^{-4}$
Seeing $\theta_{13} \neq 0$	MINOS CNGS	Conventional Superbeams Phase I	Conventional Superbeams Phase II	ν Factory $L \geq 3500\ km$
Mass Hierarchy	Combinations of Phase I Superbeams	Combinations of Phase II Super/β-beams	Combinations of ν Factory and Super/β-beams	ν Factory $L \sim 7700\ km$
Evidence for CP-violation	Combinations of Phase I Superbeams	Combinations of Phase II Super/β-beams	Combinations of ν Factory and Super/β-beams	Combinations of ν Factory 2 baselines

The first Super-Beam: off-axis T2K, from JAERI at Tokai to SK

Start 2009



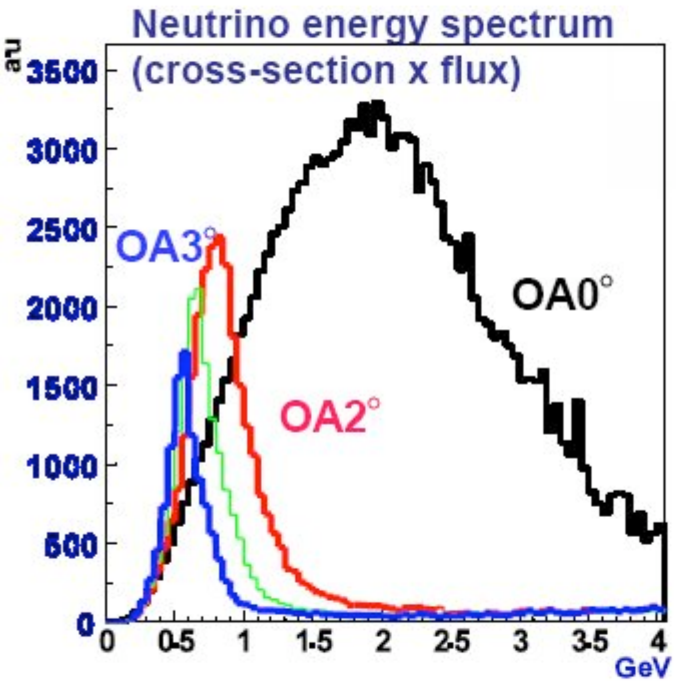
- low E_ν (<1 GeV) Super-Beam: 10^{21} pot/year
- @ 2° → 3000 ν_μ CC/year (x10 w.r.t. K2K)
- 0.2% ν_e contamination and π° BG
- SK plus three near detector sites



μ monitor (beam direction and intensity)

ν energy spectrum and intensity

Same spectrum as SK, BG measurement



Importance of near detectors: difference in near/far spectra **main systematic error in K2K**

Expected systematics in T2K:

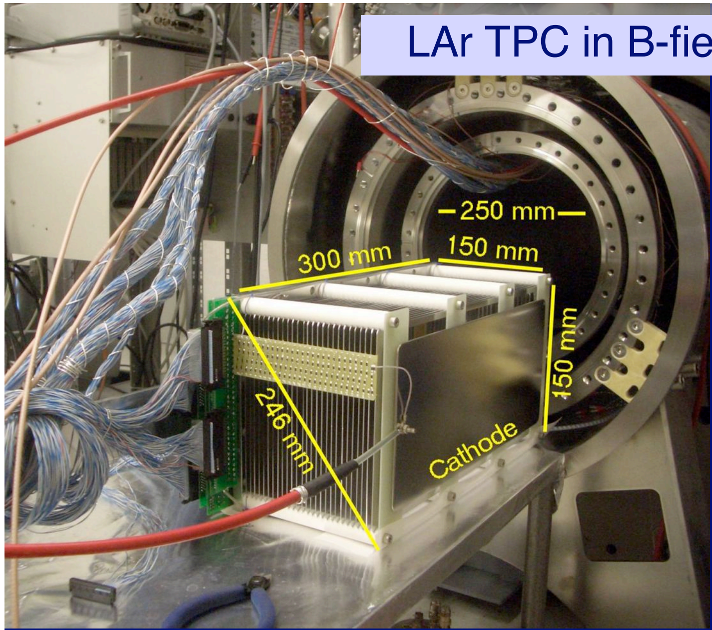
normalization	(5%)
non-qe/qe ratio	(5%)
E scale	(1%)
Spectrum shape	(20%)
Spectrum width	(5%)

A liquid Argon TPC for T2K: a mid-term goal in a global long term strategy centered on LAr TPC detectors

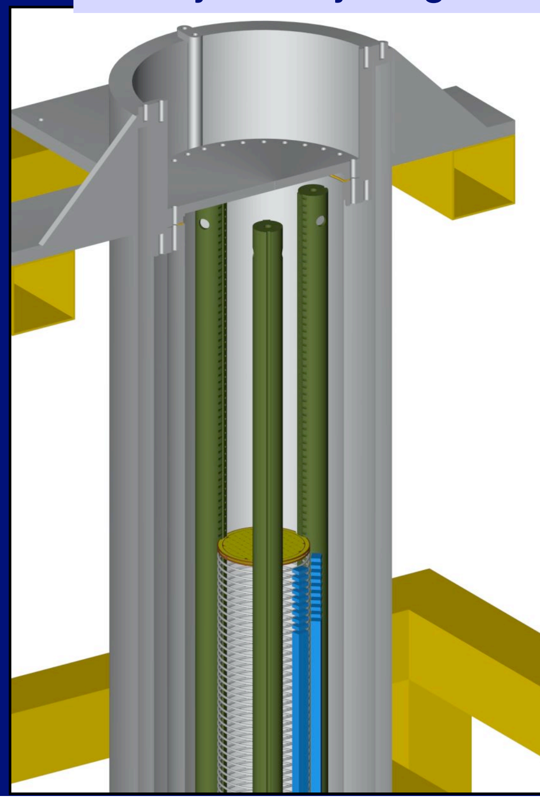
- Experiments for CP violation: a giant liquid Argon scintillation, Cerenkov and charge imaging experiment,
  A.Rubbia, Proc. II Int. Workshop on Neutrinos in Venice, 2003, Italy, hep-ph/0402110
- Ideas for future liquid Argon detectors,
  A. Ereditato and A.Rubbia, Proc. Third International Workshop on Neutrino-Nucleus Interactions in the Few GeV Region, NUINT04, March 2004, Gran Sasso, Italy, **Nucl.Phys.Proc.Suppl.139:301-310,2005**, hep-ex/0409034
- Ideas for a next generation liquid Argon TPC detector for neutrino physics and nucleon decay searches,
  A. Ereditato and A.Rubbia, Proc. Workshop on Physics with a Multi-MW proton source, May 2004, CERN, Switzerland, submitted to SPSC Villars session
- Very massive underground detectors for proton decay searches,
  A.Rubbia, Proc. XI Int. Conf. on Calorimetry in H.E.P., CALOR04, Perugia, Italy, March 2004, hep-ph/0407297
- Liquid Argon TPC: mid & long term strategy and on-going R&D,
  A.Rubbia, Proc. Int. Conf. on NF and Superbeam, NUFACT04, Osaka, Japan, July 2004
- Present status and prospects of neutrino oscillation experiments,
  A. Ereditato, Proc. of the Int. Workshop on Heavy Quarks and Flavors, S.Juan de Puertorico, June 2004, HQ &L, 73-88.
- Liquid Argon TPC: a powerful detector for future neutrino experiments,
  A.Ereditato and A. Rubbia, HIF05, La Biodola, Italy, May 2005, hep-ph/0509022
- Neutrino detectors for future experiments,
  A.Rubbia, Nucl. Phys. B (Proc. Suppl.) 147 (2005) 103.
- Conceptual Design of a scalable milti-kton superconducting magnetized liquid argon TPC,
  A. Ereditato and A. Rubbia, hep-ph/0510131.

Snapshots from some of our present R&D activities

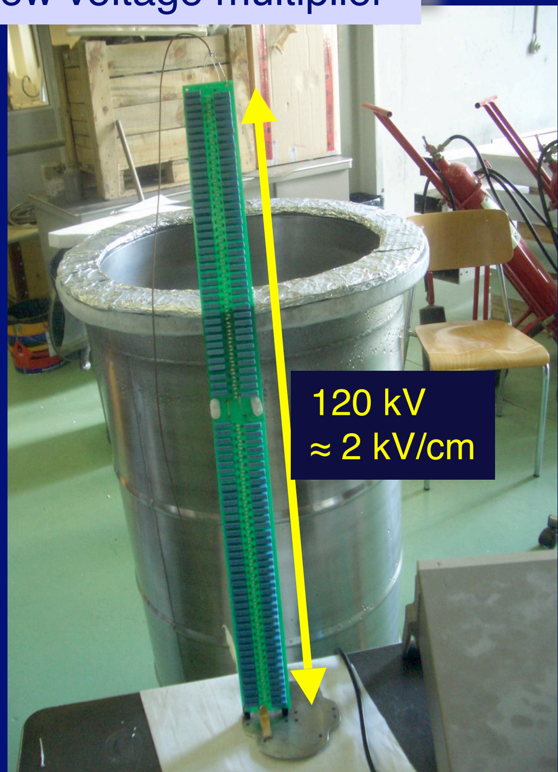
LAr TPC in B-field

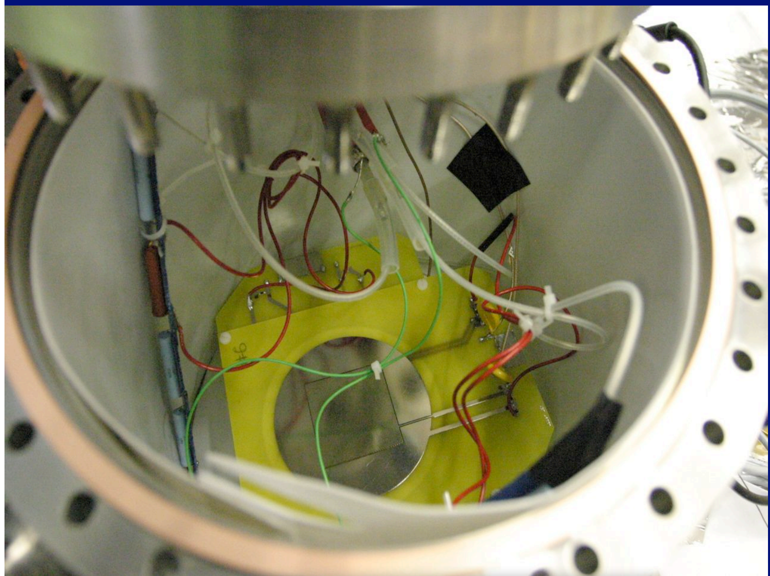


study of very long drift



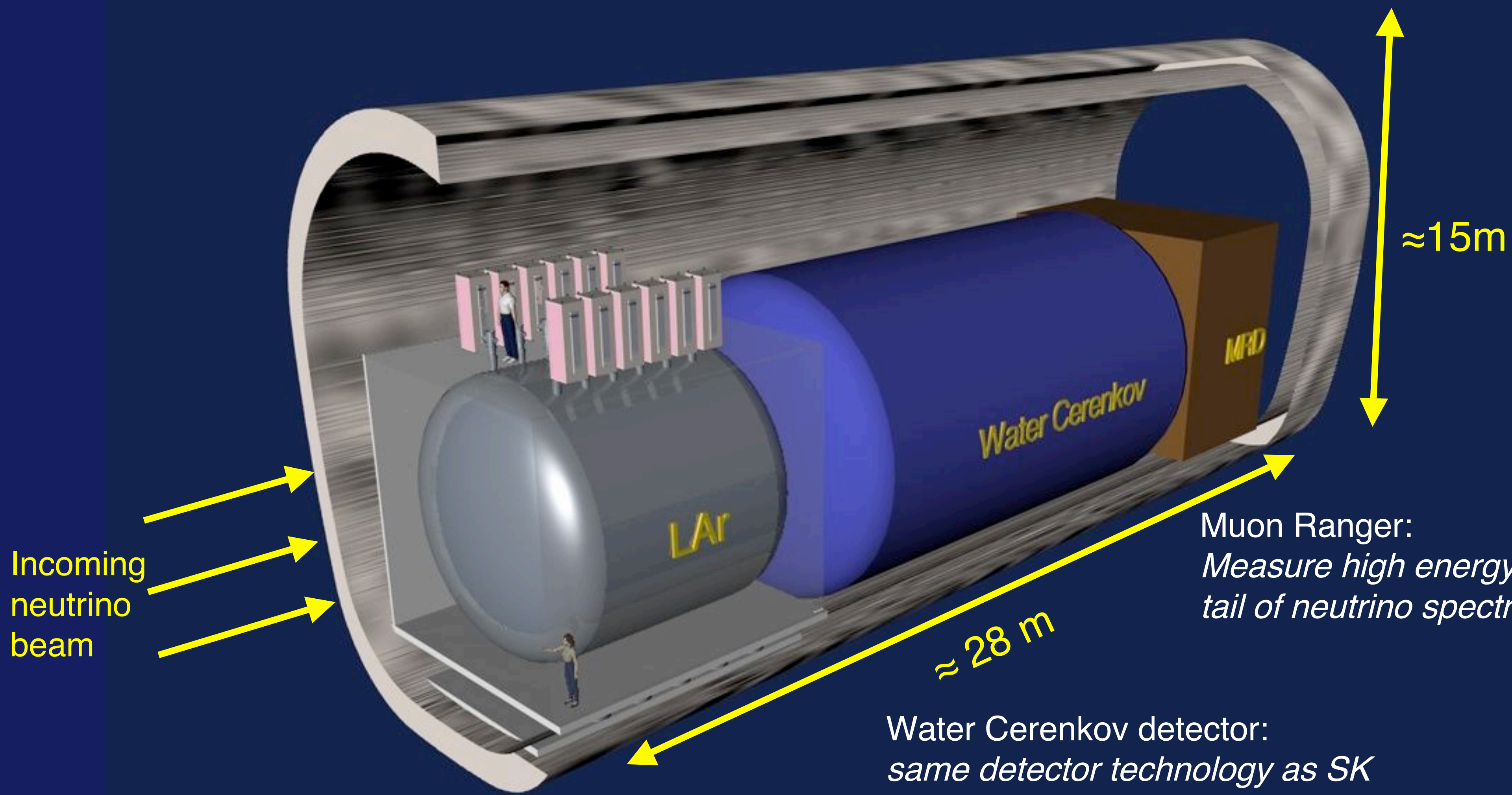
New voltage multiplier





New LEM signal readout

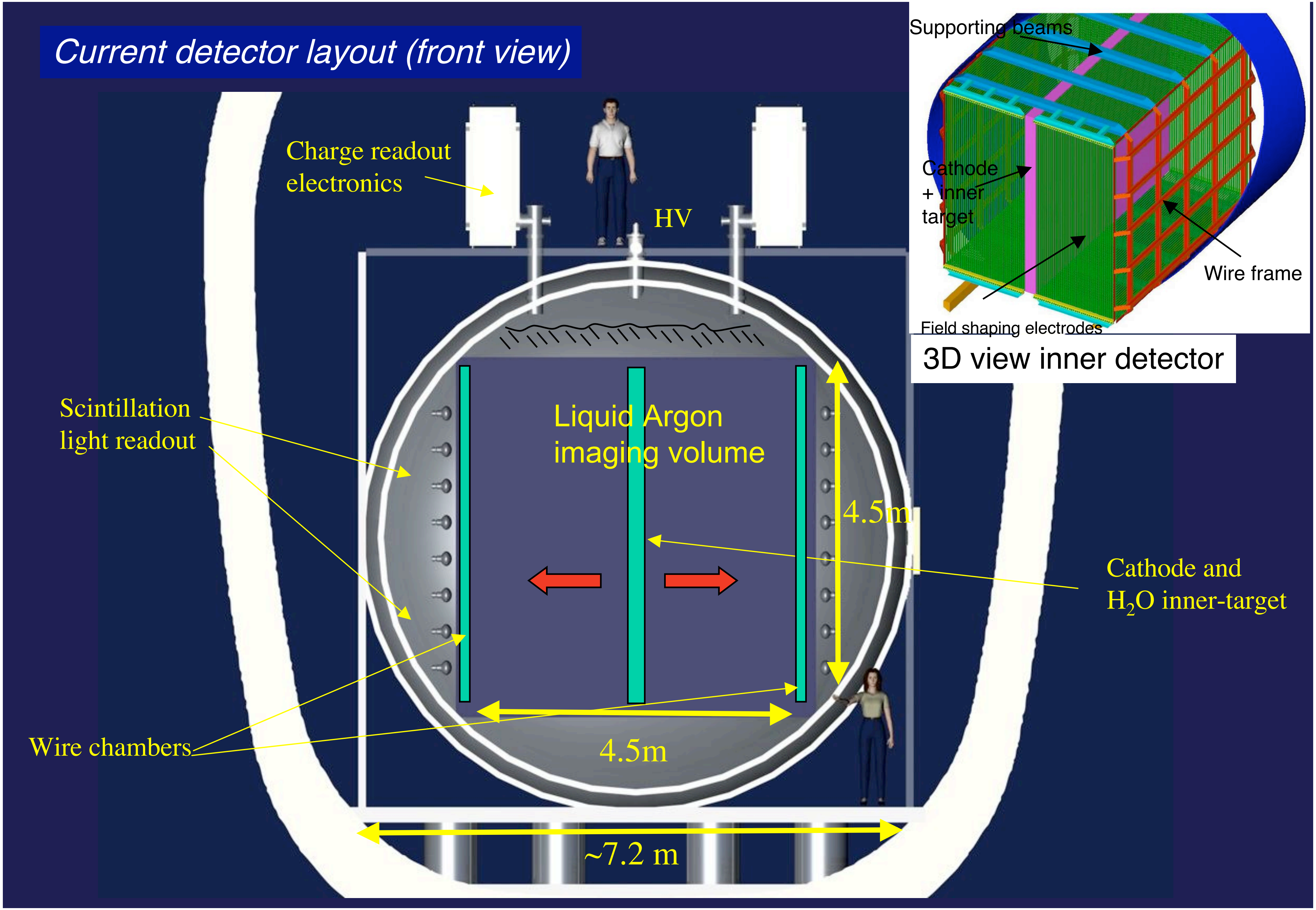
LAr TPC for the T2K 2km site: detector complex integration



Muon Ranger:
Measure high energy
tail of neutrino spectrum

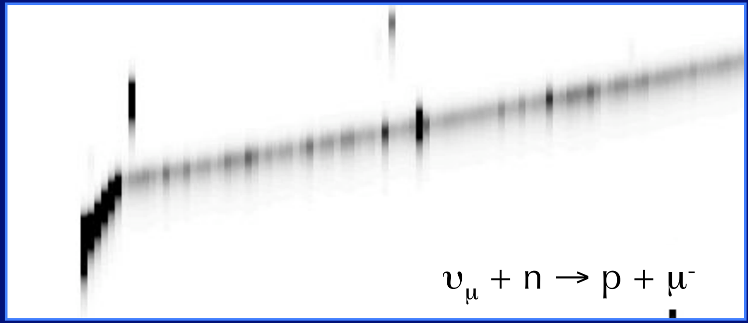
Water Cerenkov detector:
same detector technology as SK
≈1 interaction/spill/kton

Liquid Argon detector:
exclusive final states
frozen water inner-target

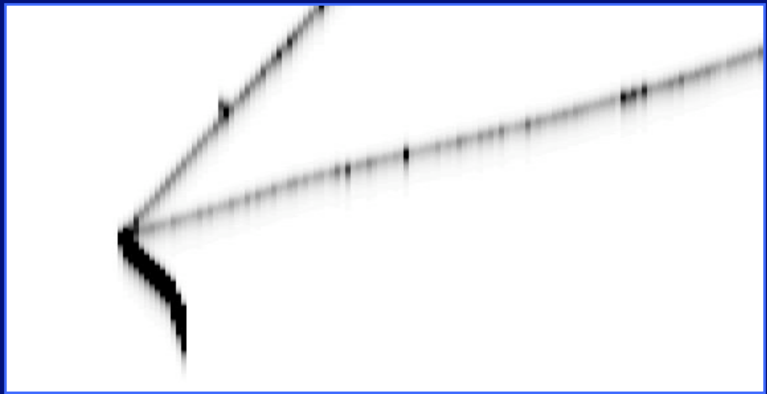

Current detector layout (front view)
Charge readout electronics
HV
Scintillation light readout
Liquid Argon imaging volume
4.5m
Cathode and H_2O inner-target
Wire chambers
4.5m
~7.2 m
Supporting beams
Cathode + inner target
Wire frame
Field shaping electrodes
3D view inner detector

Important features provided by the LAr TPC for T2K

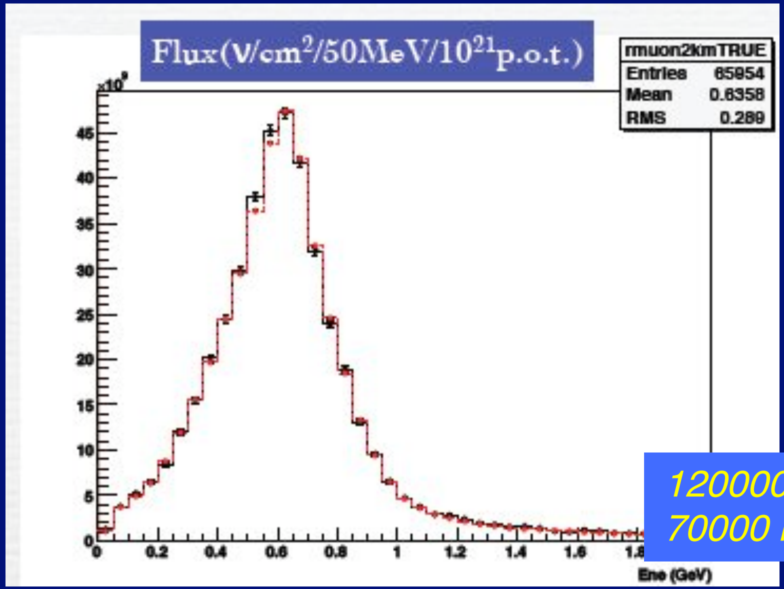
- Fully active, homogeneous, high-resolution device ⇒ fine grain detector and high statistics neutrino interaction studies with bubble chamber accuracy .
- Reconstruction of low momentum hadrons (below Cerenkov threshold), especially recoiling protons.
- Independent measurement of off-axis flux and QE/nonQE event ratio.
- Exclusive measurement of νNC events with clean π^0 identification for an independent determination of systematic errors on the NC/CC ratio.
- Measurement of the intrinsic ν_eCC background.
- Large statistical sample of neutrino interactions in the GeV region for the study of quasi-elastic, deep-inelastic and resonance modelling and of nuclear effects.



MC QE event
Proton momentum = 490 MeV/c



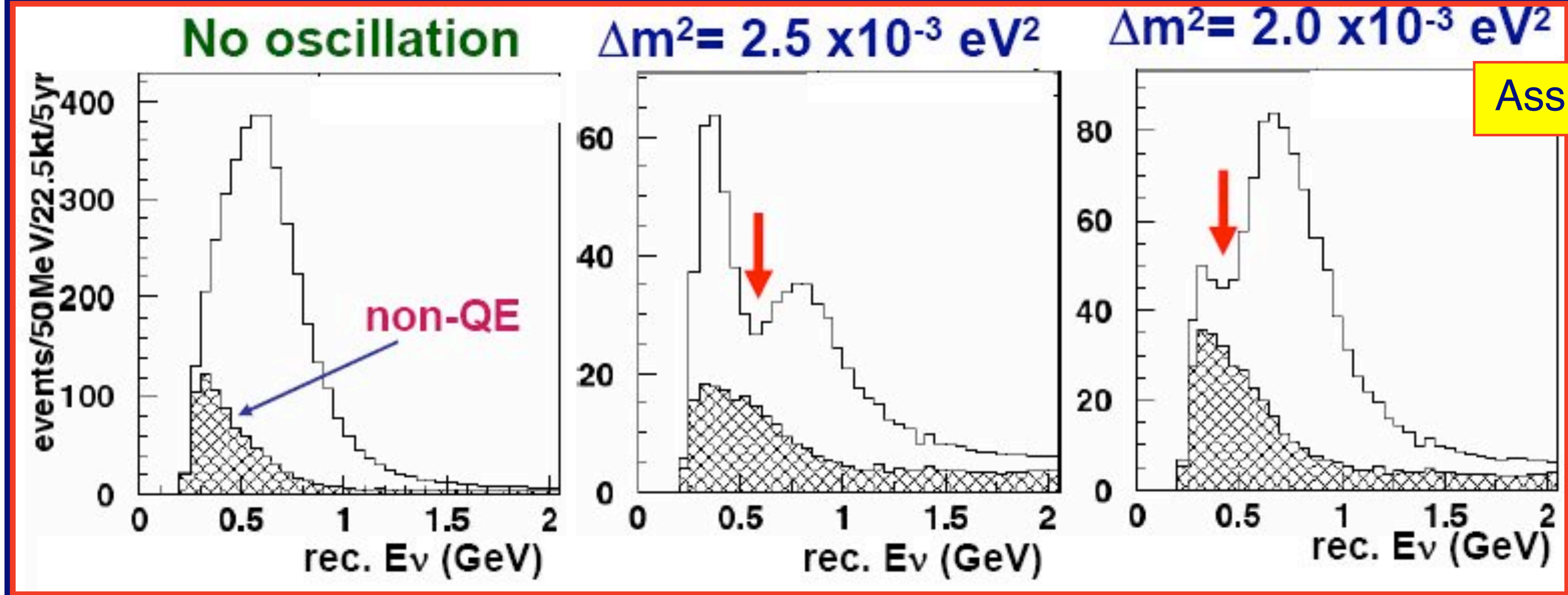
MC nQE event
Pion momentum = 377 MeV/c,
Proton momentum = 480 MeV/c



120000 QE events/yr
70000 non-QE events/yr

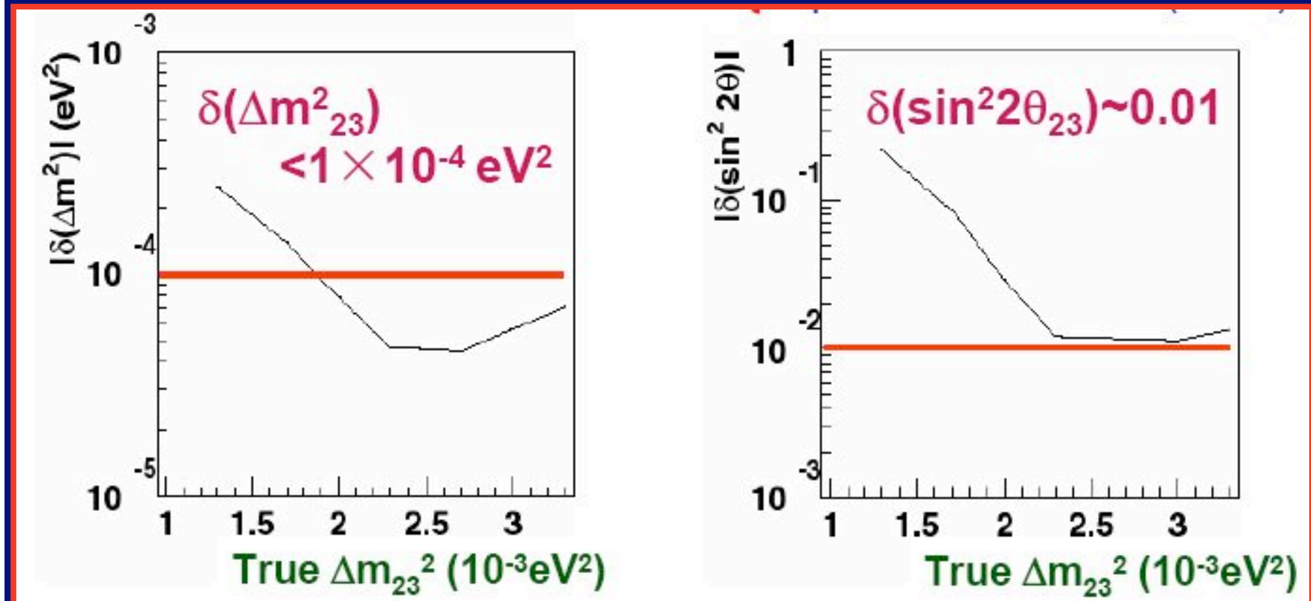
T2K ν_μ disappearance

$$P(\nu_\mu \rightarrow \nu_x) \sim 1-\cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2(\Delta m^2_{23}L/4E)$$



Assume $\theta_{23} = \pi/4$

5 years running

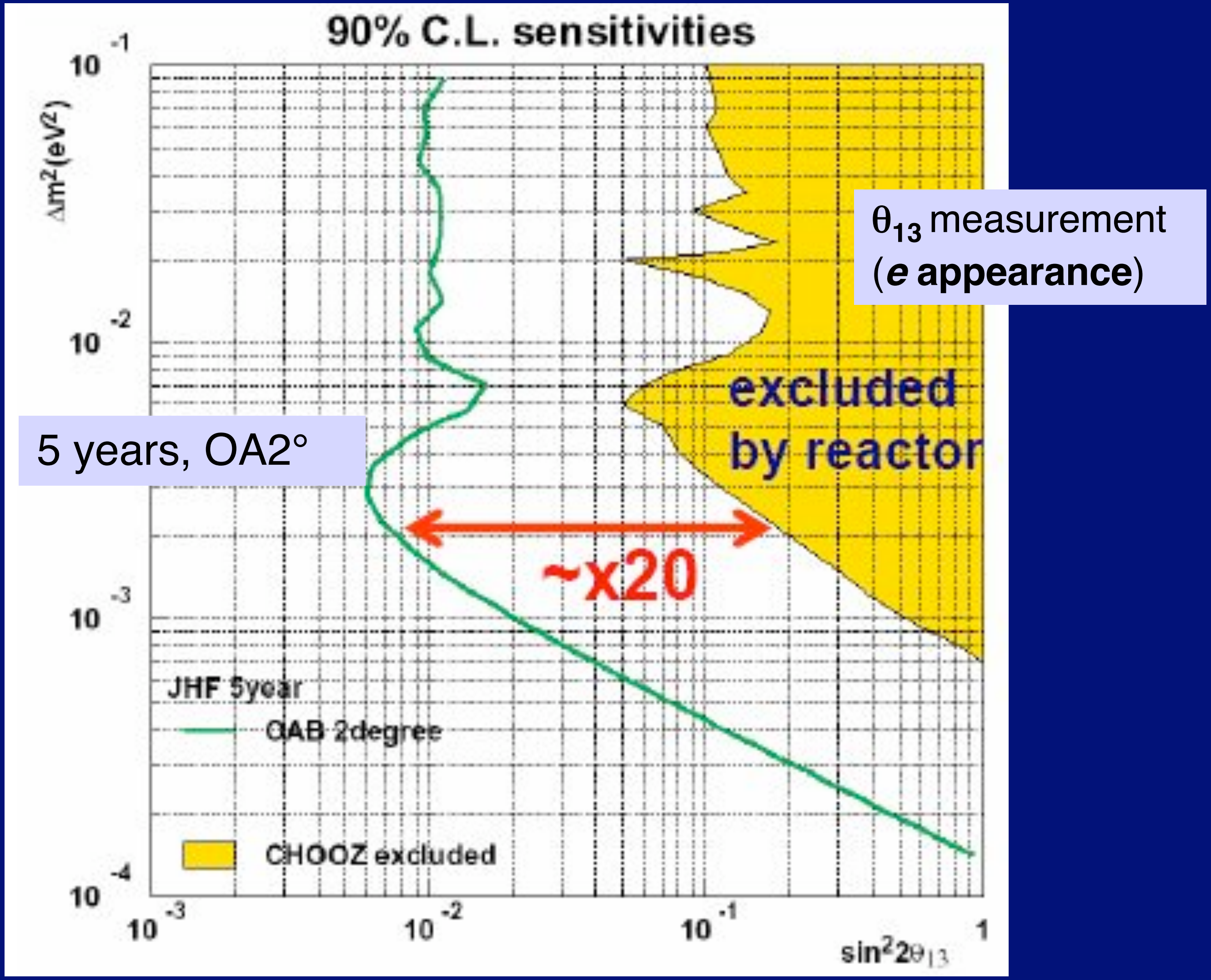


Harvest for T2K (~2013-2014)

- determine Δm^2_{23} with an uncertainty of **10^{-4}**
- know if $\sin^2 2\theta_{23} = 1$ with an uncertainty of **0.01**
- appearance: evidence for non-zero $\sin^2 2\theta_{13}$ if larger than **0.018** (90% CL limit at **0.006**)

T2K ν_e appearance: measurement of θ_{13}

$$P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{23} L/4E)$$



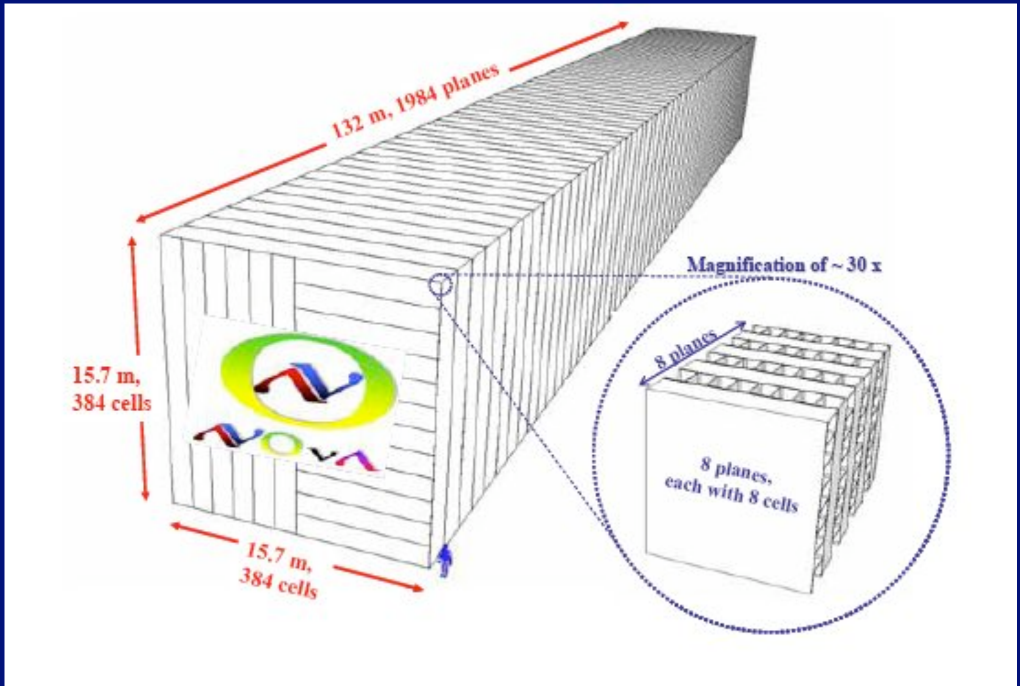
Sensitivity:

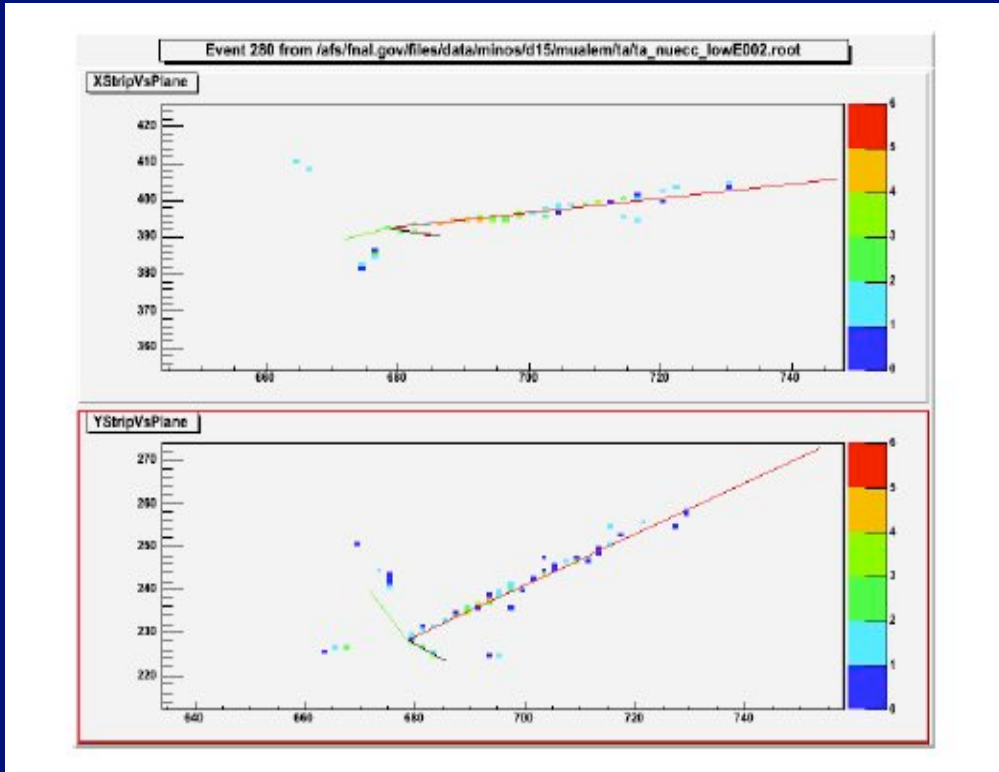
$\sin^2 2\theta_{13} > 0.006$ (90%)
$\sin^2 2\theta_{13} > 0.018$ (3σ)

An off-axis experiment in the NuMI beam: NoνA

Start 2010-2011 (?)

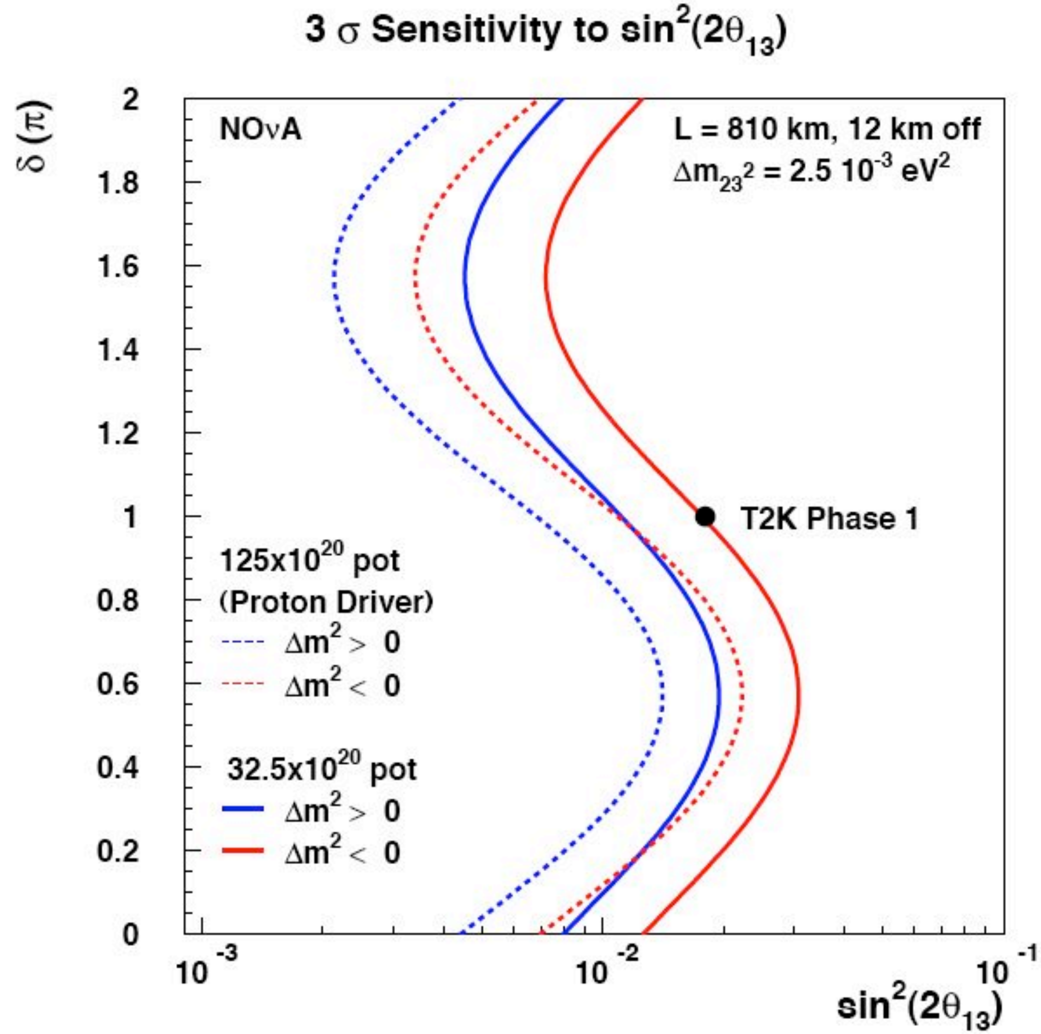
- proposal, approval phase; nominal NuMI beam: 0.4 MW + upgrade?
- if approved: small fraction of the far detector by 2008. Completed by end 2011 (?)
- far detector: 30 kton @ Ash River (MN) 810 km from Fermilab (12 km, 14 mrad off-axis)
- technique: fine grained calorimeter (liquid scintillator) with fiber/APD R/O
- near detector: same as far, 1 ton fiducial mass
- unlike T2K, NovA is sensitive to matter effects, but is a single task detector (cost ~ $200 M)





ν_e **CC event**

Sensitivity of NOνA to the measurement of $\sin^2 2\theta_{13}$



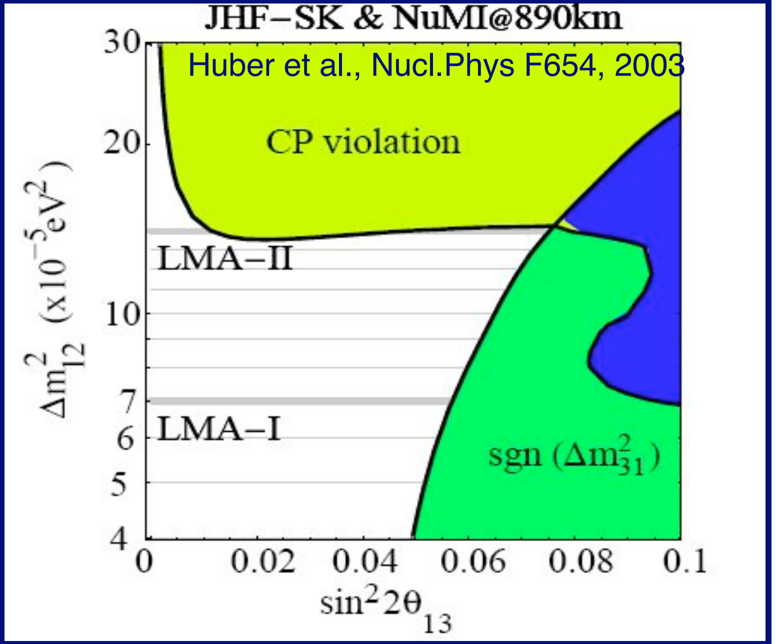
Comparison between MINOS, T2K and NoνA

Assume 5 years running, Δm^2_{23}= 2.5 x 10^{-3} eV^2, 3σ evidence for non zero $\sin^2 2\theta_{13}$:

Experiment	Run	p.o.t.	3σ evidence
MINOS	2005-2008	16 x 10^{20}	> 0.080
T2K	2009-2013	50 x 10^{20}	> 0.018
NoνA (Booster) NoνA (p driver)	2011-2015 ?	32.5 x 10^{20} 125 x 10^{20}	> 0.018 (0.012) > 0.012 (0.006)

• The Japanese project has an **existing** far detector and an **approved** beam (in construction): **possibility of discovery**

With some chance, next generation experiments on θ_{13} could measure mass hierarchy and CP effects



Pin down CP phase and mass hierarchy

e.g. : detecting CP violating effects

Best method:
(in vacuum)

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

it <u>requires</u>: Δm^2_{12} and $\sin 2\theta_{12}$ large (LMA solar): OK !

larger effects for long L: 2nd oscillation maximum

however…

$$P(\nu_\mu \to \nu_e) \propto \sin^2 2\theta_{13} \qquad A_{CP} \propto \frac{1}{\sin\theta_{13}}$$

$\sin^2 2\theta_{13}$ small: low statistics and large asymmetry

$\sin^2 2\theta_{13}$ large: high statistics and small asymmetry

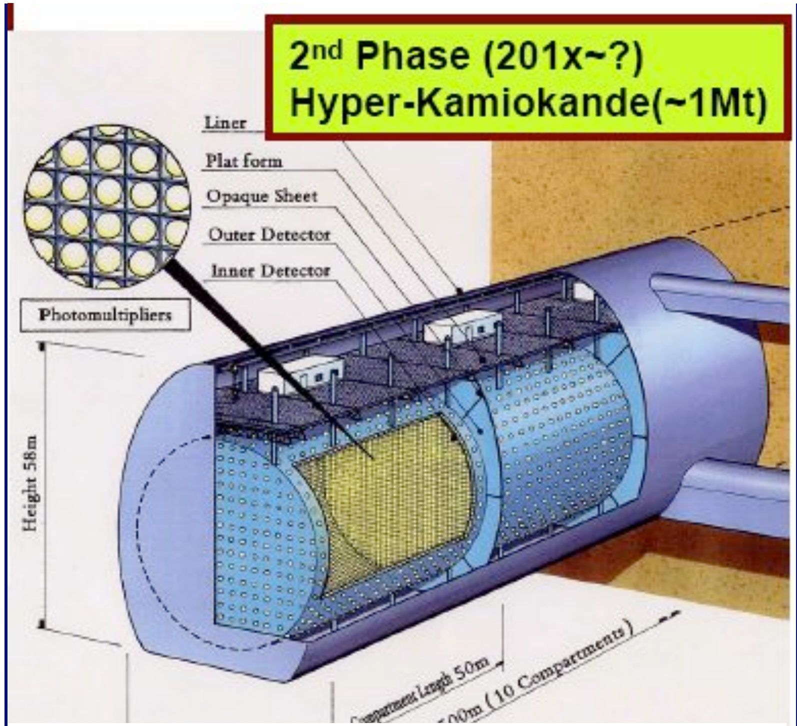
impact on the detector design

…and:

$$P(\nu_\mu \to \nu_e) \propto \sin^2 \frac{\Delta m^2_{23} L}{4E}$$

oscillations are governed by Δm^2_{atm} , L and E:
E ≈ 5 GeV → L ≈ 3000 km

flux too low with a conventional LBL beam



2 det: 48m x 50m x 250m each

DETECTORS

500-1000 kton Water Cerenkov ‘a la SK’ (Hyper-K, UNO) are considered as a ‘natural’ option

Rationale: exploit a well known technique
aim at a ‘reasonable’ cost

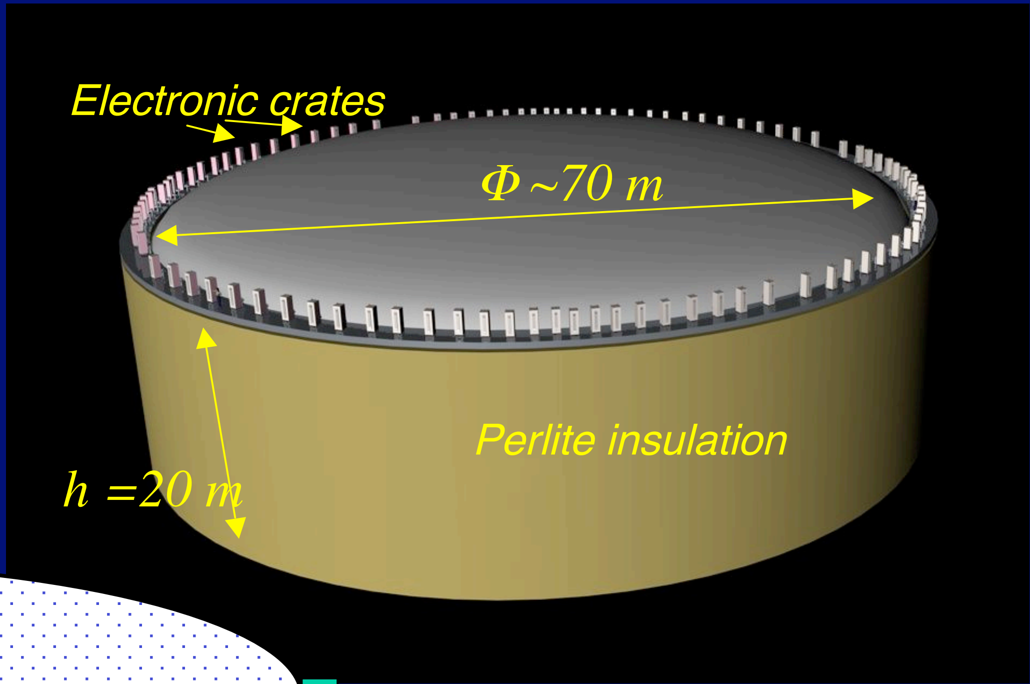
However, this is not the only possibility...

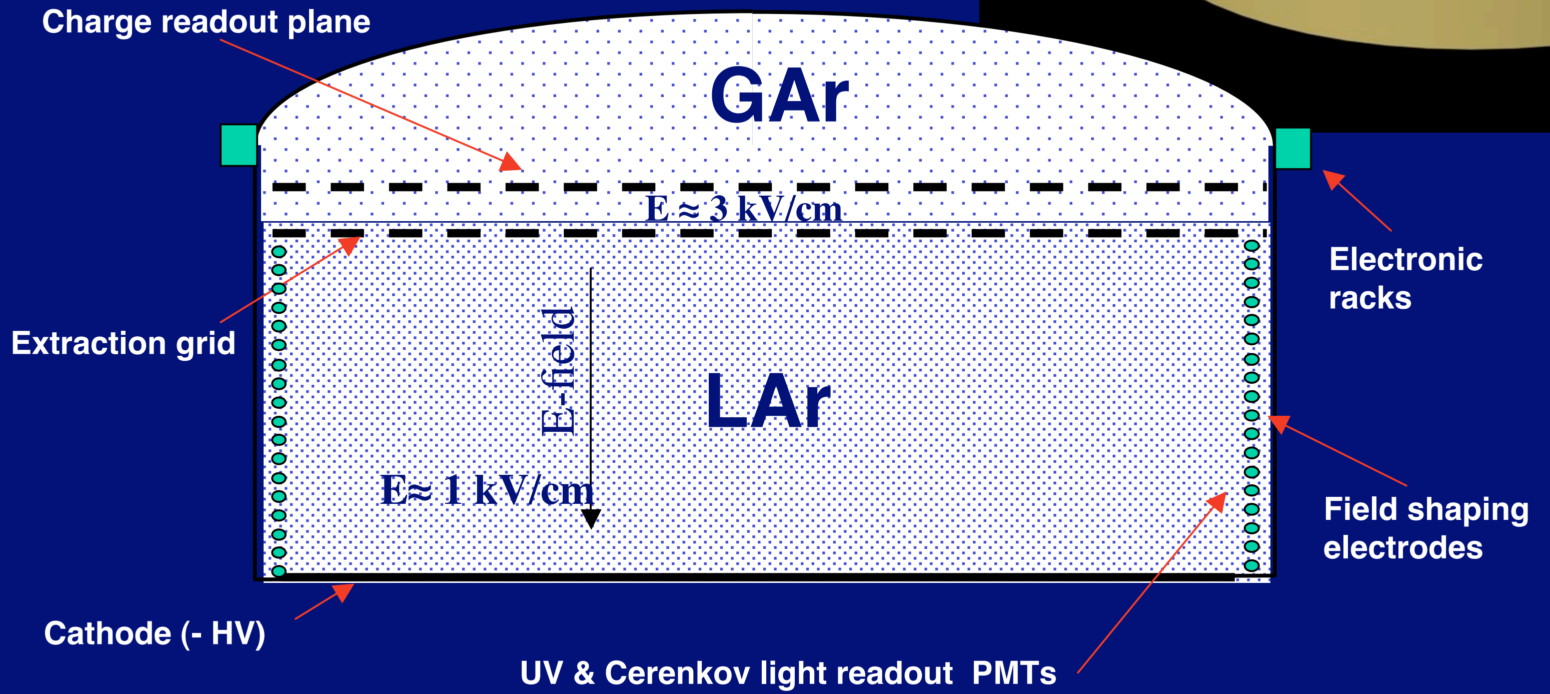
Water Cerenkov technique

- efficient for ‘few’ or 1-ring events (QE), small x-section, large detector mass
- good π^0 rejection if γ are well separated
- at low energy confusion between μ and π tracks
- can go down with energy threshold (5 MeV for 40% coverage) ?
- well established in Japan: success of SK but limited experience elsewhere
- Hyper-K project well advanced: decision around 2012 ?
- PMTs: leadership of Hamamatsu (very large production will be required)
- alternative photo-detectors options unclear: R&D & cost assessment needed
- huge cavern: cost and complexity of excavation works

A fine grained detector can be alternative/complementary: liquid Argon TPC

- LAr TPC: imaging with bi-phase R/O
- LNG tanker technology
- ~100 kton LAr
- auto-refrigerating

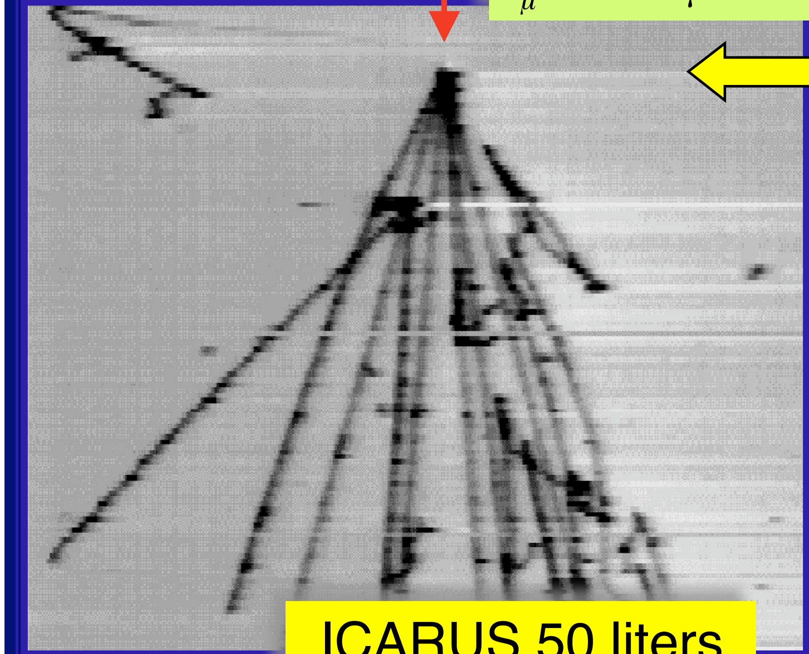




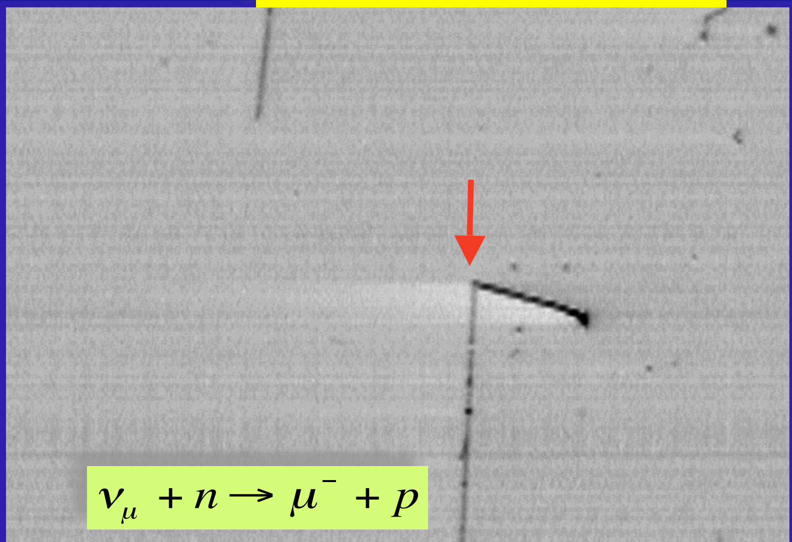
Neutrino detection: LAr TPC vs water Cerenkov

$$\nu_\mu + X \rightarrow \mu^- + many\ \ prongs$$

Multi prong event detection not possible with water Cerenkov

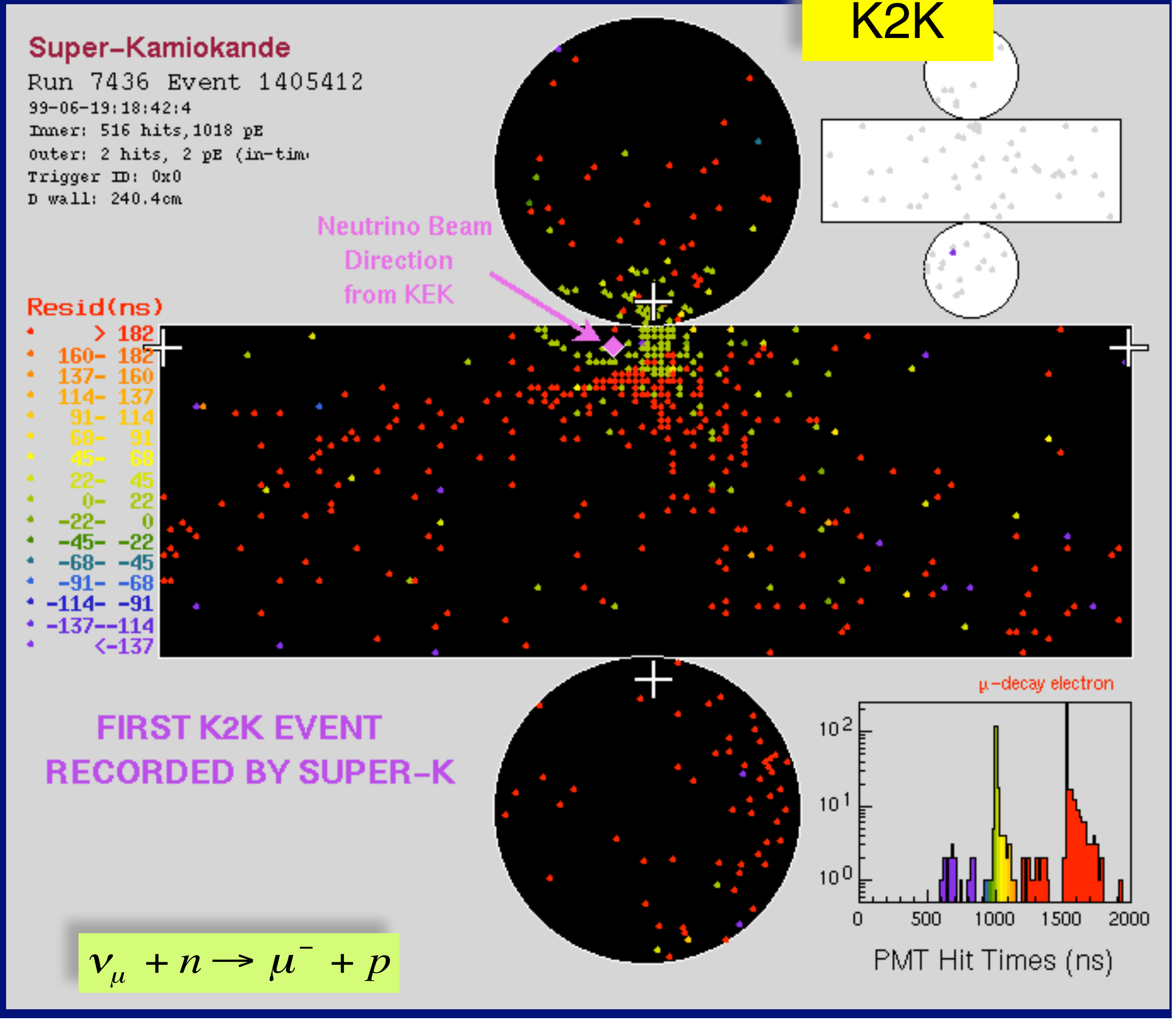


ICARUS 50 liters



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

K2K



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

	Water Cerenkov (UNO)	Liquid Argon TPC
Total mass	650 kton	100 kton
Cost	≈ 500 M$	Under evaluation
$p \rightarrow e\,\pi^0$ in 10 years	10^{35} years ε = 43%, ≈ 30 BG events	3×10^{34} years ε = 45%, 1 BG event
$p \rightarrow \nu\,K$ in 10 years	2×10^{34} years ε = 8.6%, ≈ 57 BG events	8×10^{34} years ε = 97%, 1 BG event
$p \rightarrow \mu\,\pi\,K$ in 10 years	No	8×10^{34} years ε = 98%, 1 BG event
SN cool off @ 10 kpc	194000 (mostly $\bar{\nu}_e p \rightarrow e^+ n$)	38500 (all flavors) (64000 if NH-L mixing)
SN in Andromeda	40 events	7 (12 if NH-L mixing)
SN burst @ 10 kpc	≈330 ν-e elastic scattering	380 ν_e CC (flavor sensitive)
SN relic	Yes	Yes
Atmospheric neutrinos	60000 events/year	10000 events/year
Solar neutrinos	E_e > 7 MeV (central module)	324000 events/year (E_e > 5 MeV)

Operation of a 100 kton LAr TPC in a future neutrino facility:

Super-Beam: 460 ν_μ CC per 10^{21} 2.2 GeV protons @ L = 130 km

Beta-Beam:15000 ν_e CC per 10^{19} ^{18}Ne decays with γ = 75

Japanese program phase 2: short L, low E

Start < 2020 ?

- intensity up to 4 MW
- detector fiducial mass ~ 0.5 Mton
- no matter effects: assume mass hierarchy determined elsewhere

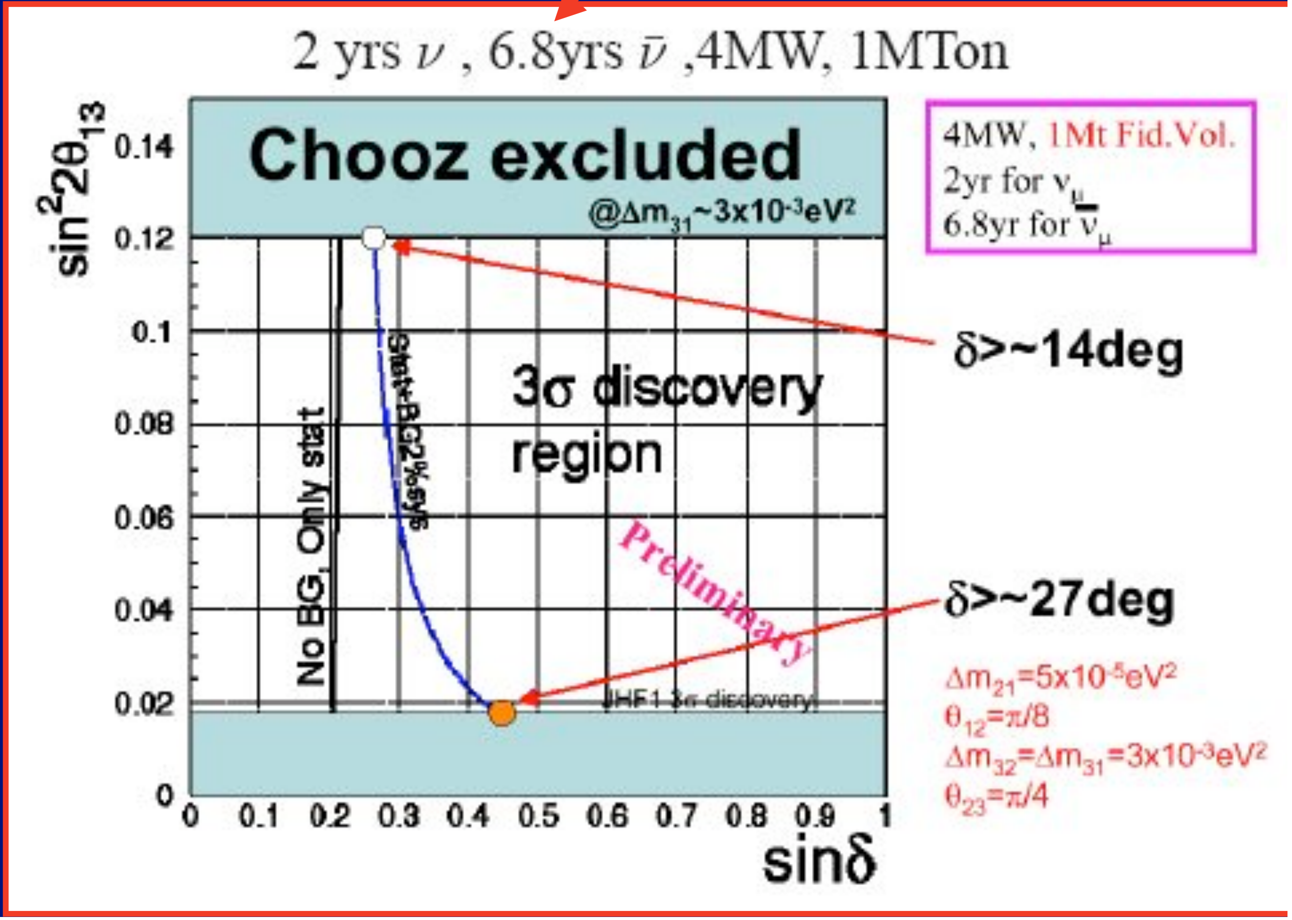
Major T2K beam upgrade, new Hyper-K detector

1) low energy: low $\pi°$ BG

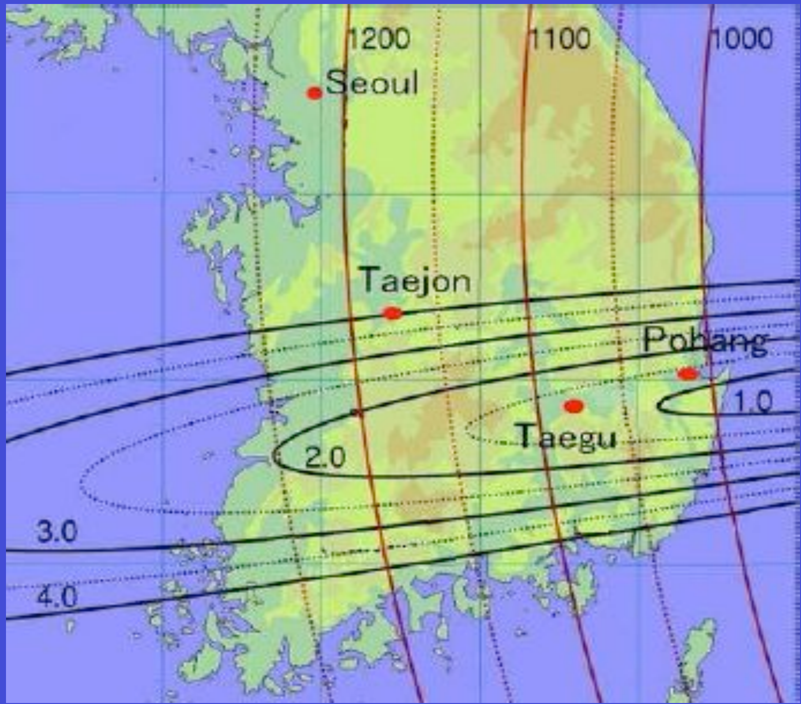
2) gigantic water Cerenkov: good *e* ID

demanding requirements: 2% syst. from BG subtraction and 2% from data selection

low $E\bar{\nu}$ → low x-section



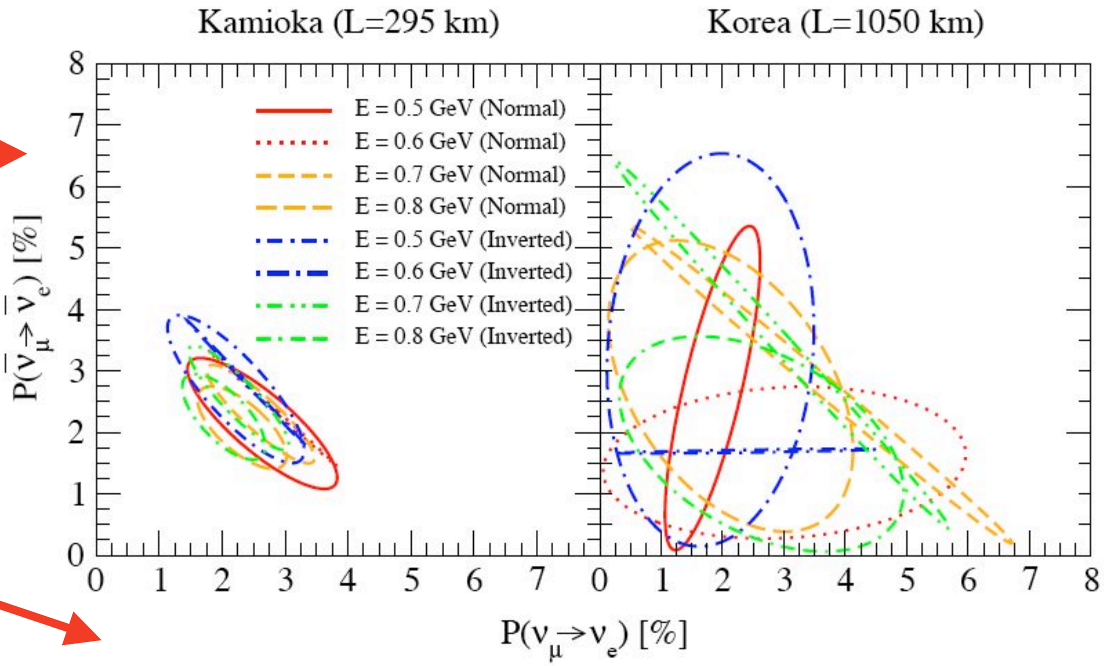
T2KK option: two detectors (270 kton each) in Japan and Korea



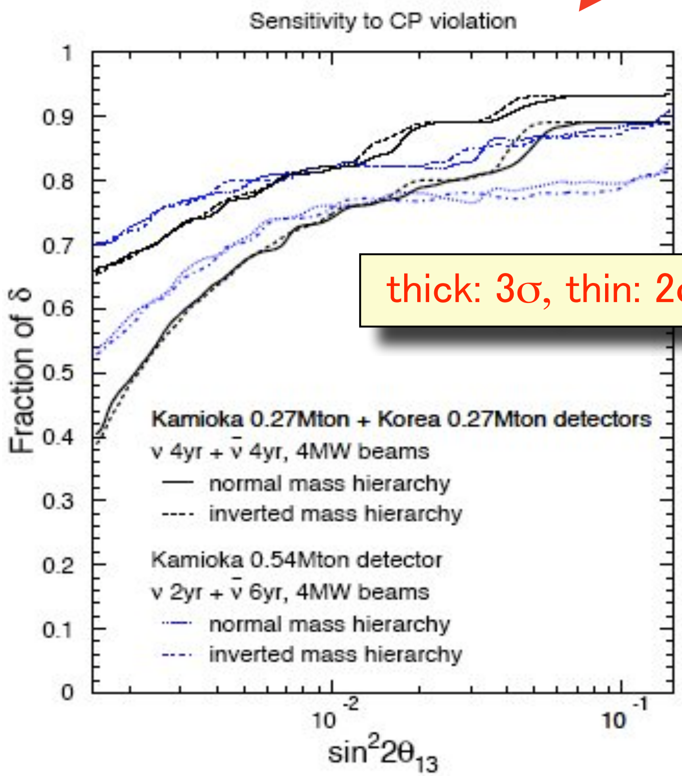
Interesting option:

- sensitivity to matter effects
- systematic errors largely cancel
- solve ambiguities
- build two smaller detectors
- share cost of construction (Japan-Korea collaboration)

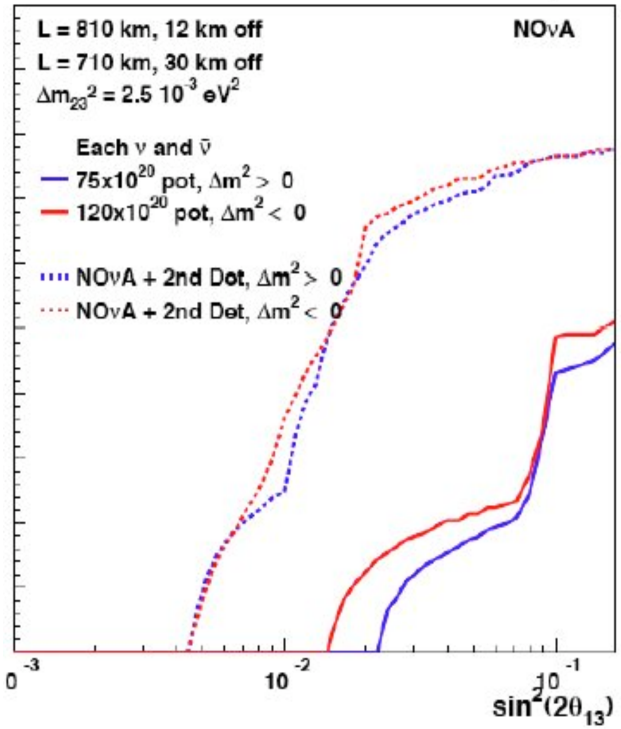
HK vs T2KK



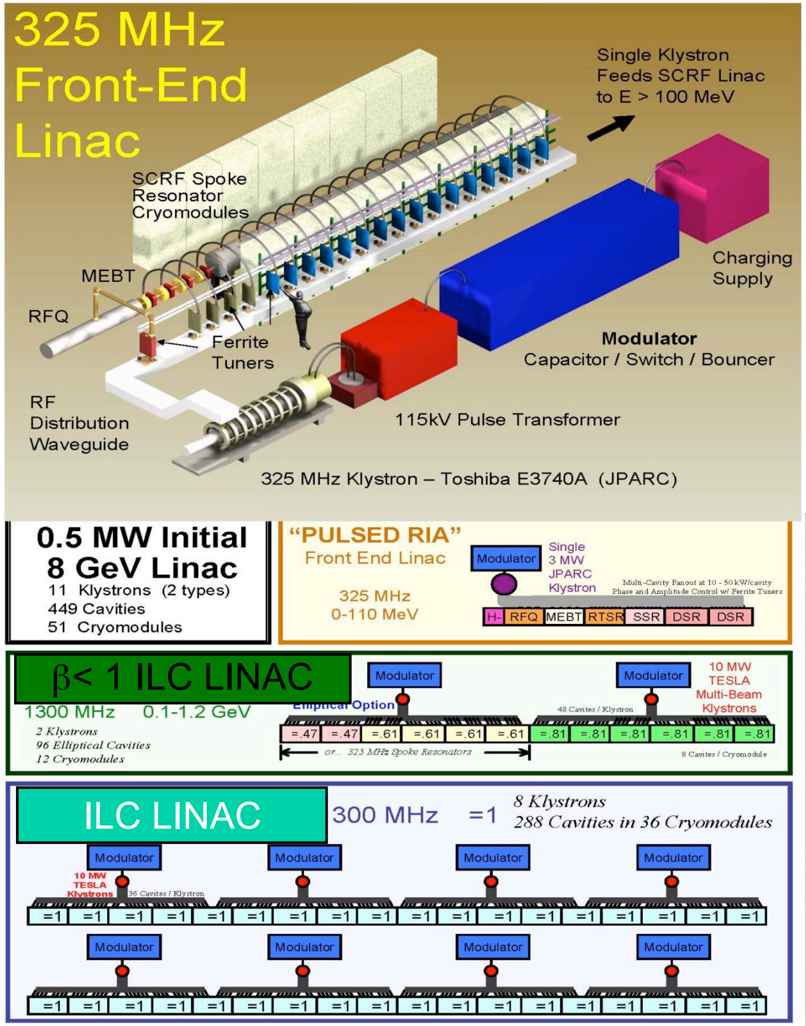
CP violation sensitivity: T2KK vs NOvA

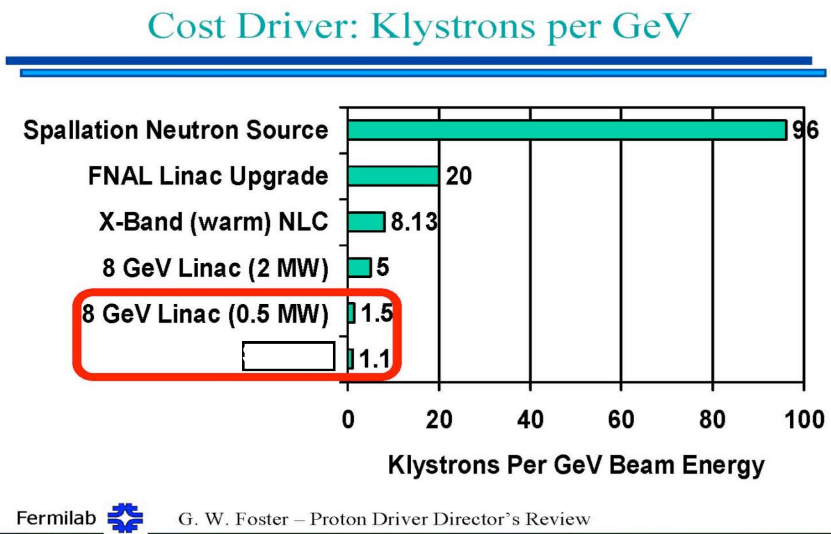


thick: 3σ, thin: 2σ

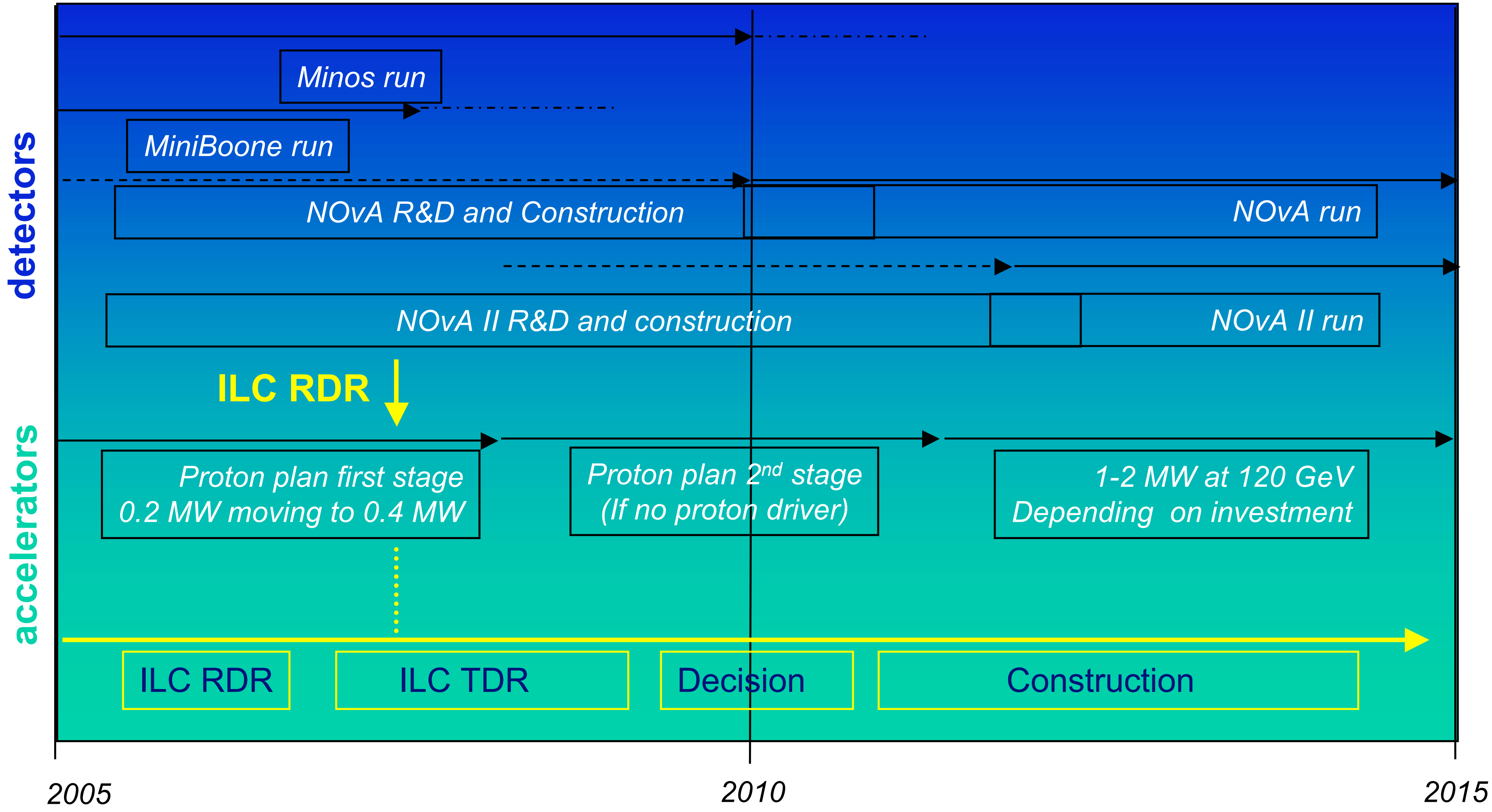


US options: e.g. FERMILAB project (high intensity proton driver)



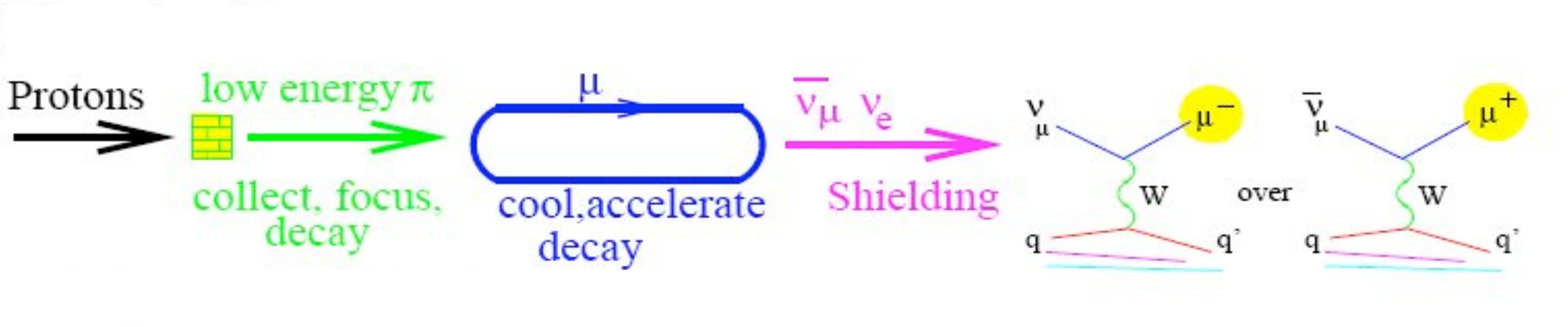


FERMILAB plans for neutrino physics (from P.Oddone)



Proton driver construction might be anticipated if ILC would be delayed

Neutrino Factories…the ultimate neutrino beam experiments?

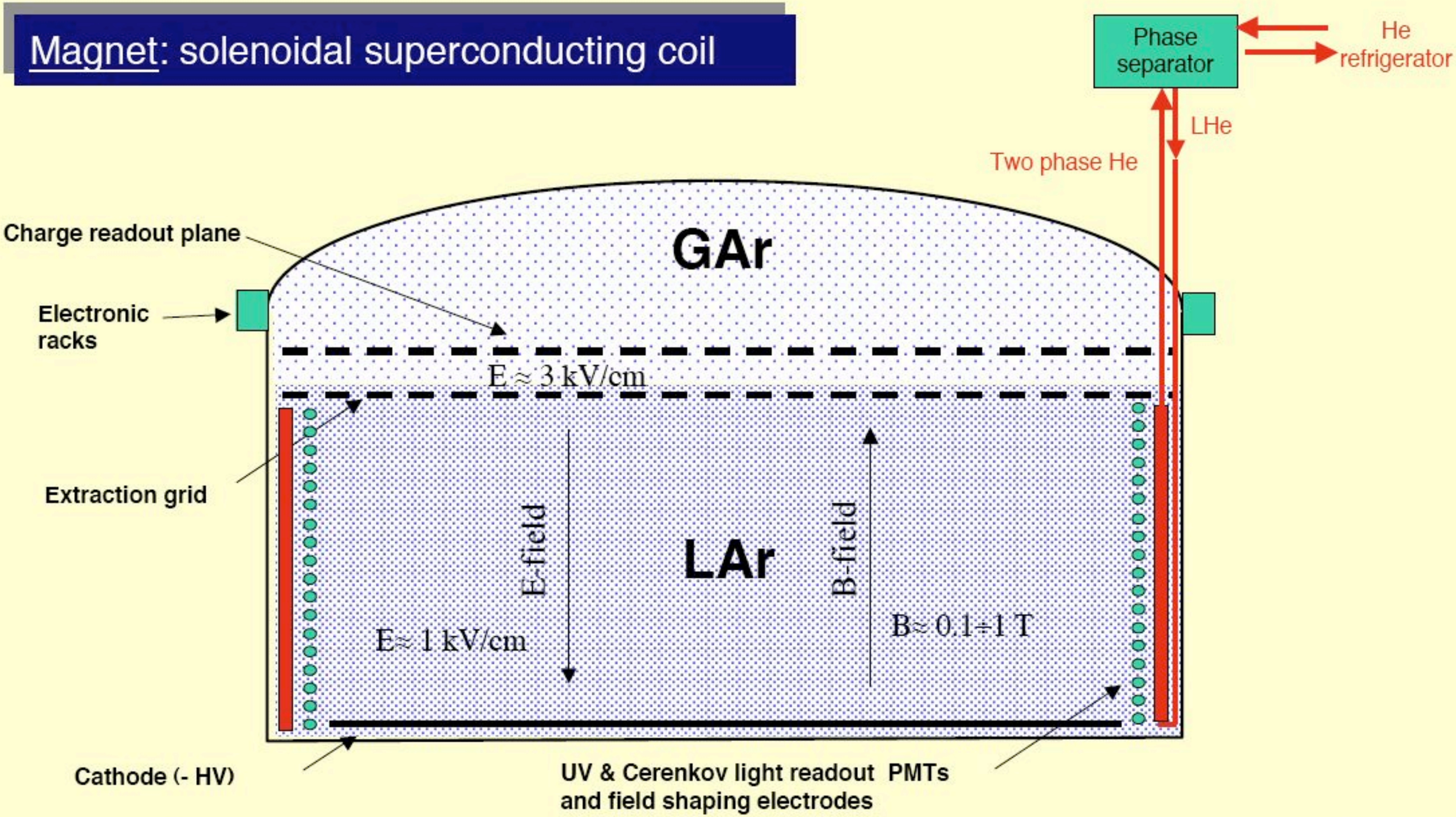


Obviously, a great opportunity for neutrino physics!

- huge neutrino fluxes, increasing with muon energy
- Eν may range from 5 to 30 GeV, 10^{20} muon decays/year
- only two flavors for a given polarity: $\bar{\nu}_\mu$ and ν_e or ν_μ and $\bar{\nu}_e$
- for a massive, coarse-resolution set-up: μ detection easier than *e* ID over $\pi°$ BG (wrong sign muons)
- possible to use large mass detectors already exploited for Super- Beta- Beams (magnetic analysis)
- detector can be simple, but don't forget unexpected, new physics events to be studied in great detail
- in principle 'very' low beam- and detector-BG
- L from ~ 1000 to 8000 km (international enterprise by definition!)
- very complex accelerator facility: R&D needed and being pursued worldwide (EU, USA, Japan)
- the first accelerator stage could be a proton driver for a Super-Beam
- extremely challenging project: target, muon cooling, radiation and environmental issues, cost, etc.

Tentative layout of a large magnetized GLACIER

Magnet: solenoidal superconducting coil



LHe Cooling: Thermosiphon principle + thermal shield=LAr

(personal) concluding remarks

- **The glory of the massive neutrino!** The evidence for neutrino oscillation is today very robust. This has opened the way to precision studies of the mixing matrix with **accelerator** neutrino experiments, together with future projects on direct mass measurements, double-beta decay, reactor, solar and atmospheric neutrinos. The mass of neutrino is the first (and so far the only) indication of **physics beyond the SM**.

- Running and planned experiments will contribute to **narrow-down the errors** on the oscillation parameters and with some chance to prove that the mixing matrix is indeed 3 x 3. The next generation will need high intensity facilities to pin down a non vanishing value of θ_{13}. Advanced detector technique will be required to keep BG low for a real improvement of the sensitivities. This physics subject is of **outstanding importance** 'per se' but also because it will drive future initiatives.

- The detection of **matter** and of **CP violating effects** will likely require a further generation of experiments using high intensity (>1 MW) neutrino facilities with more massive detectors. Detector options: a 500-1000 kton **water Cerenkov** detectors (à la SK), 50-100 kton **liquid Argon TPCs**, large **liquid scintillator** detector.

- In addition to the need of large mass, the detectors have to be **'general purpose'** (think of tomorrow's physics), must have good energy resolution (measure oscillation parameters), good granularity (to measure channels involving e, μ, τ,…) and adequate NC/CC separation for BG suppression. They will need to be as good for **astroparticle physics** (underground or at shallow depth) and they have to employ cost effective technical solutions/technologies.

(personal) concluding remarks (cont.)

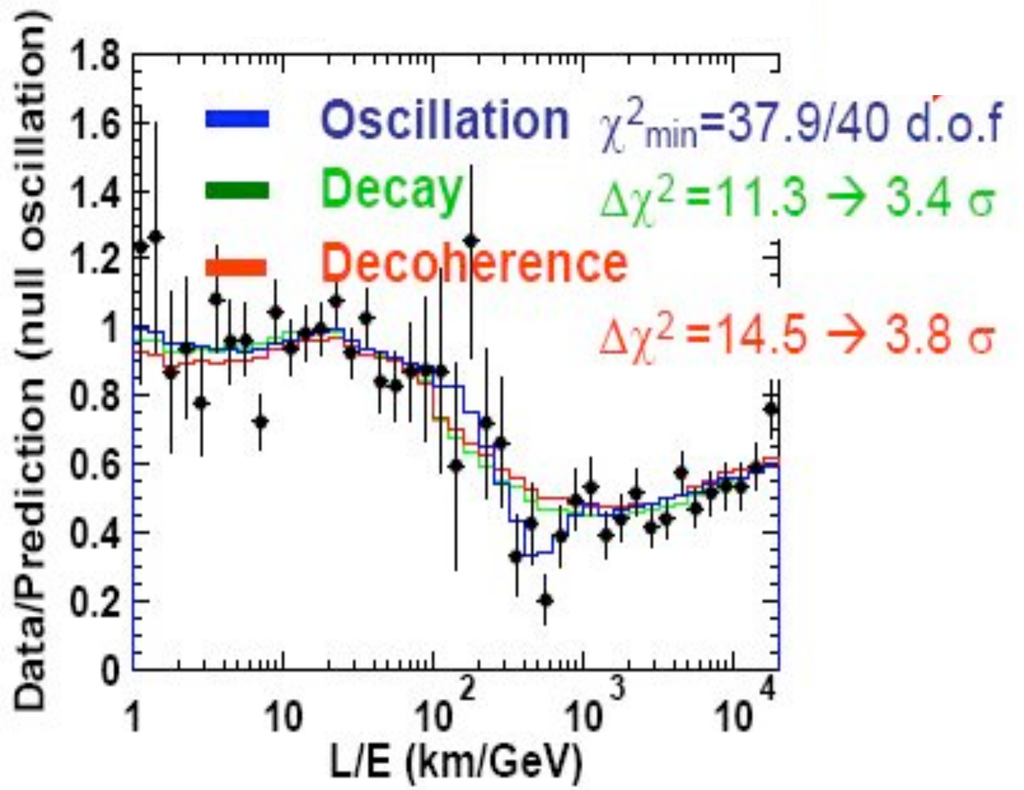
- Concerning the **neutrino beams**, a factor ~10 boost in the intensity is required. **Super-Beams** are the natural approach, based on improved LINAC or Boosters. Synergies are expected with other fields and this can increase the probability of success (funding). Another possibility is given by **Beta-Beams** (of low and/or high energy) complementary to other approaches (μ appearance). Regardless the neutrino source, the final choice of L/E must come from a global, **physics driven optimization** of facility and detector. A **Neutrino Factory** can be considered for a more distant future and constitutes the ultimate neutrino facility with unprecedented features but its construction would represent a huge investment for the entire community. Its main task must be the precision study of **CP violation**.

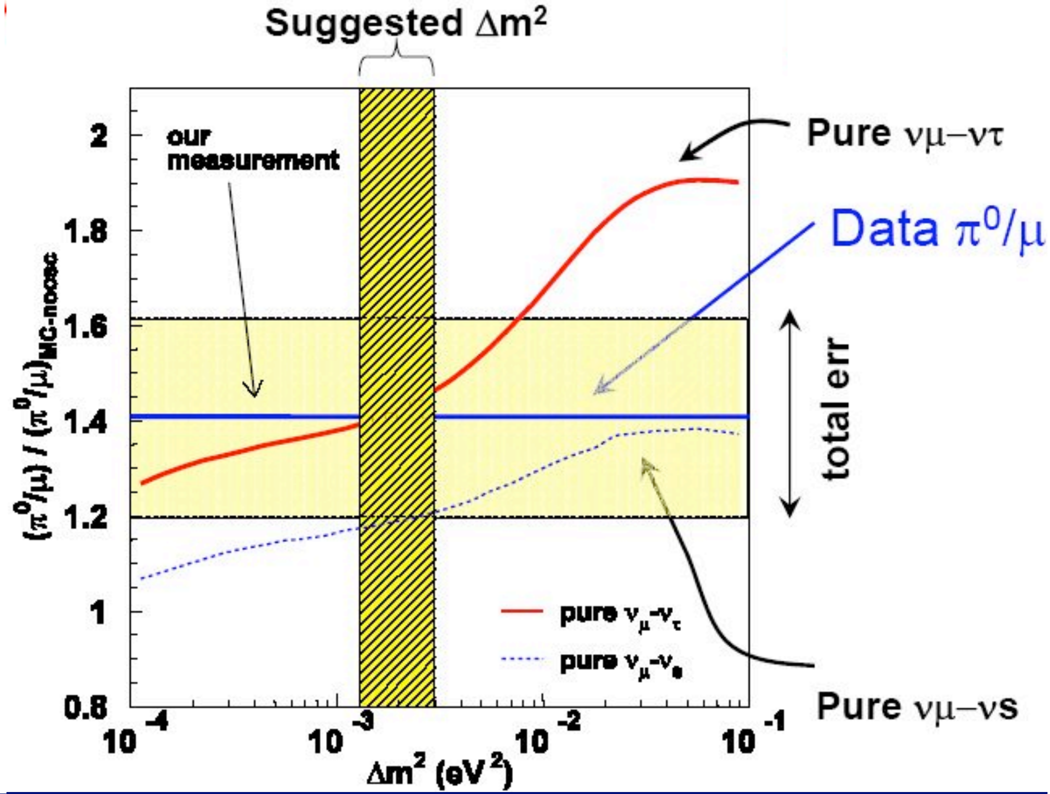
- The **cost and the complexity** of these projects demand a **strong worldwide coordinated effort** between researchers and agencies, similarly to what occurs in other fields, *e.g.* for collider physics. **Complementarity** of approaches and techniques is mandatory. Choices on projects beyond the experiments presently running or being built must pragmatically take into account (and use, as far as possible) **existing facilities** and infrastructure (detectors, beams).

- In one sentence: a lot of work (and fun) ahead of us!

Additional slides

e.g. SK atmospheric neutrinos: L/E distribution
(for selected high-resolution events) and NC/CC ratio (τ or sterile neutrino ?)





→ models alternative to oscillation are disfavored by more than 3σ

atmospheric neutrino deficit is due to $\nu_\mu \rightarrow \nu_\tau$ oscillations (not to generic conversion)

Mass hierarchy from matter oscillations

Neutrinos oscillating through matter (MSW effect):

- different behavior of different flavors due to the presence of electrons in the medium
- additional phase contribution to that caused by the non zero mass states.
- asymmetry between neutrinos and antineutrinos even without CP violating phase in the matrix
- the related oscillation length L_M, unlike L_V (vacuum), is independent of the energy
- as an example L_M (rock) is ~ 10000 km while L_M (Sun) ~ 200 km

In the limit of Δm^2_{sol} approaching zero (for which there are no CP effects) and of running at the atmospheric oscillation maximum, the asymmetry between neutrinos an antineutrinos equal to

$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} = \frac{2E_\nu}{E_R} \quad \text{for low } E_\nu$$

with

$$E_R = \frac{\Delta m^2_{atm}}{2\sqrt{2}G_F\rho_e} \approx 11GeV$$

By the measurement of this asymmetry one can determine whether Δm^2_{23} is positive or negative (hierarchy)

$$\sin^2 2\theta_{13} \quad \Rightarrow \sin^2 2\theta_{13}\left(\frac{\Delta m^2_{13}}{\Delta m^2_{13} \pm 2\sqrt{2}G_F N_e E_\nu}\right)^2$$

$$|\Delta m^2_{13}| \quad \Rightarrow |\Delta m^2_{13} \pm 2\sqrt{2}G_F N_e E_\nu|$$