resent status of neutrino mixing and masses om oscillation experiments: what future ?

Napoli, 9 December 2004

Antonio Ereditato

Where are we now ?

What do we know 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) > ~ 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 ?)

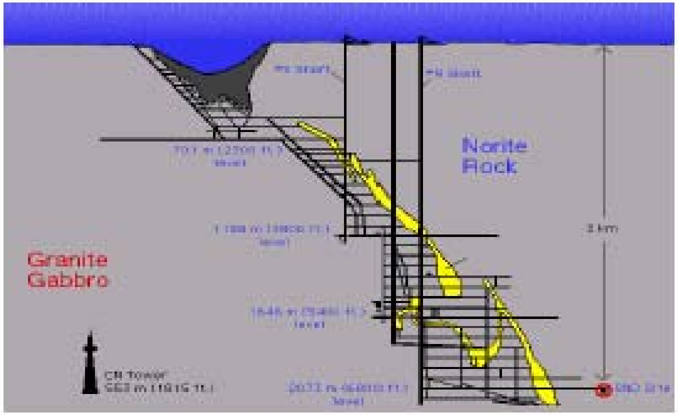
why θ_{12} and θ_{23} angles are large and θ_{13} seems very small or null ?

is mass hierarchy the same as for charged leptons (sign of Δm^2_{23})

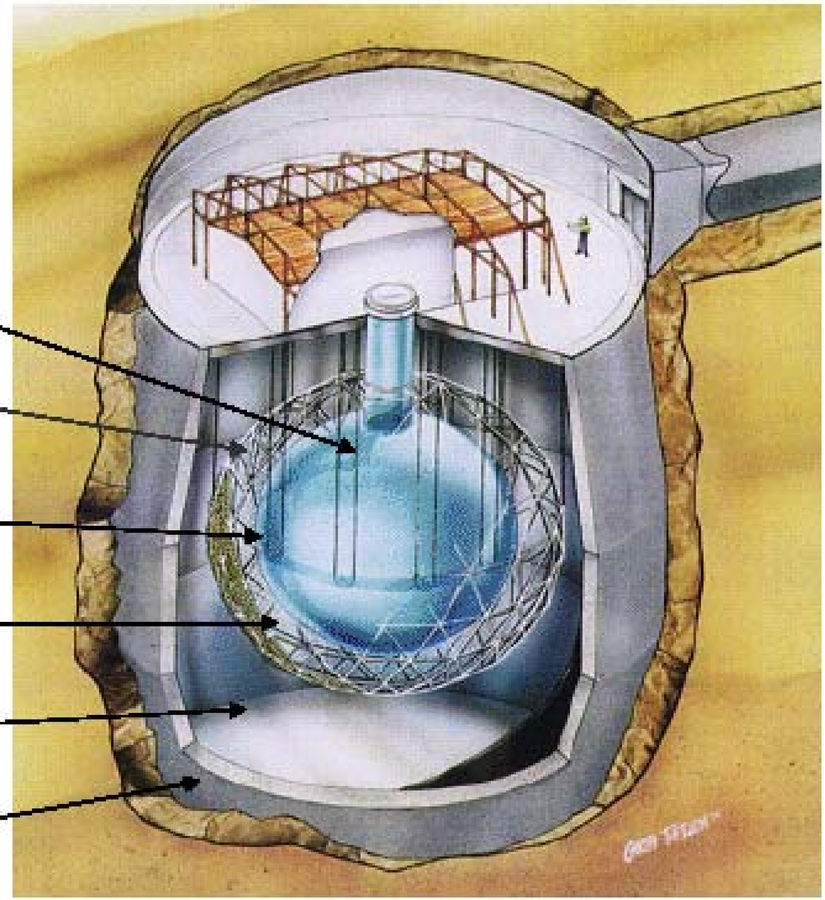
is there any CP violating phase in the mixing matrix ?

NOTE: assumed that there is no LSND effect ! Wait for MiniBoone…

The Sun vs θ_{12} and Δm^2_{12}



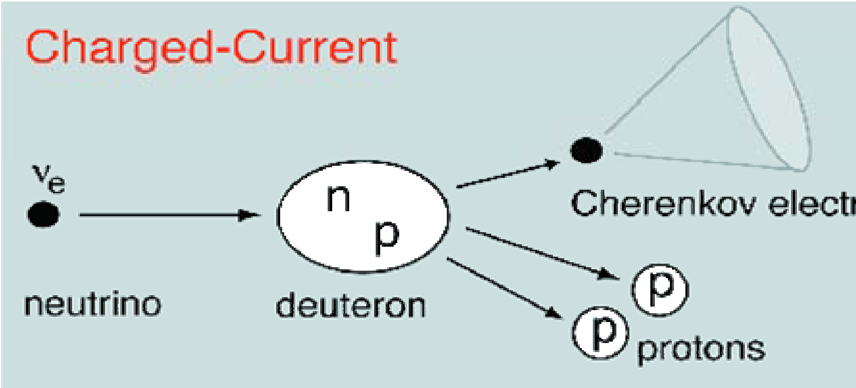
Sudbury Neutrino Observatory



Neutrino Reactions in SNO

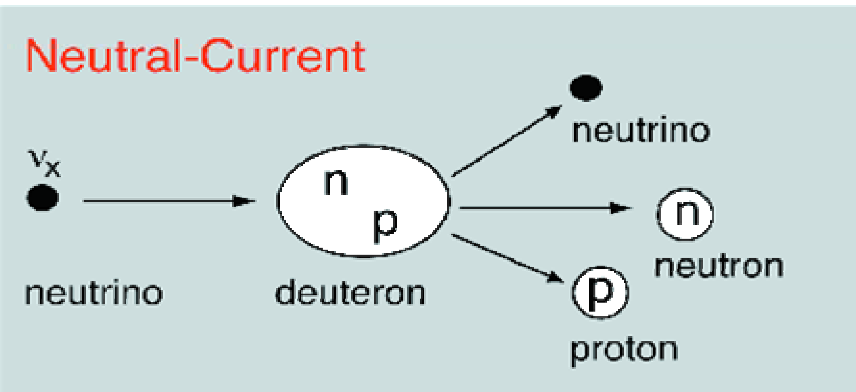
CC $\nu_e + d \rightarrow p + p + e^-$

- Q = 1.445 MeV
- good measurement of ν_e energy spectrum
- some directional info $\propto$ (1 – 1/3 cosθ)
- ν_e only



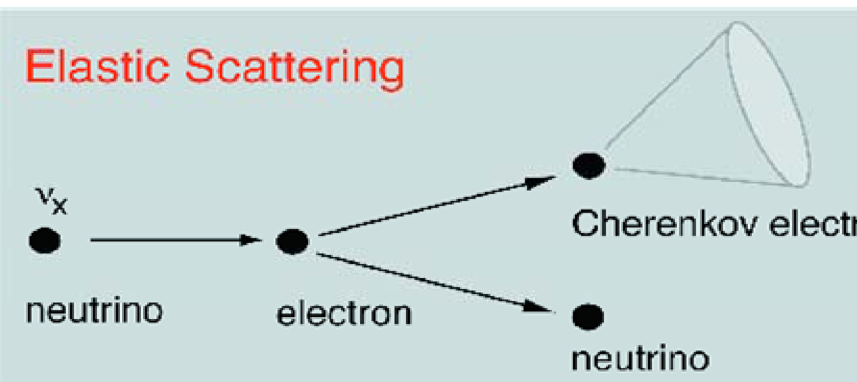
NC $\nu_x + d \rightarrow p + n + \nu_x$

- Q = 2.22 MeV
- measures total ^{8}B ν flux from the Sun
- equal cross section for all active ν flavors



ES $\nu_x + e^- \rightarrow \nu_x + e^-$

- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity



SNO analysis

wo possibilities:

$$\frac{\mathrm{CC}}{\mathrm{NC}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

Advantages:

- NC gives total flux directly
- Cross section uncertainties cance

$$\frac{\mathrm{CC}}{\mathrm{ES}} = \frac{\nu_e}{\nu_e + 0.14(\nu_\mu + \nu_\tau)}$$

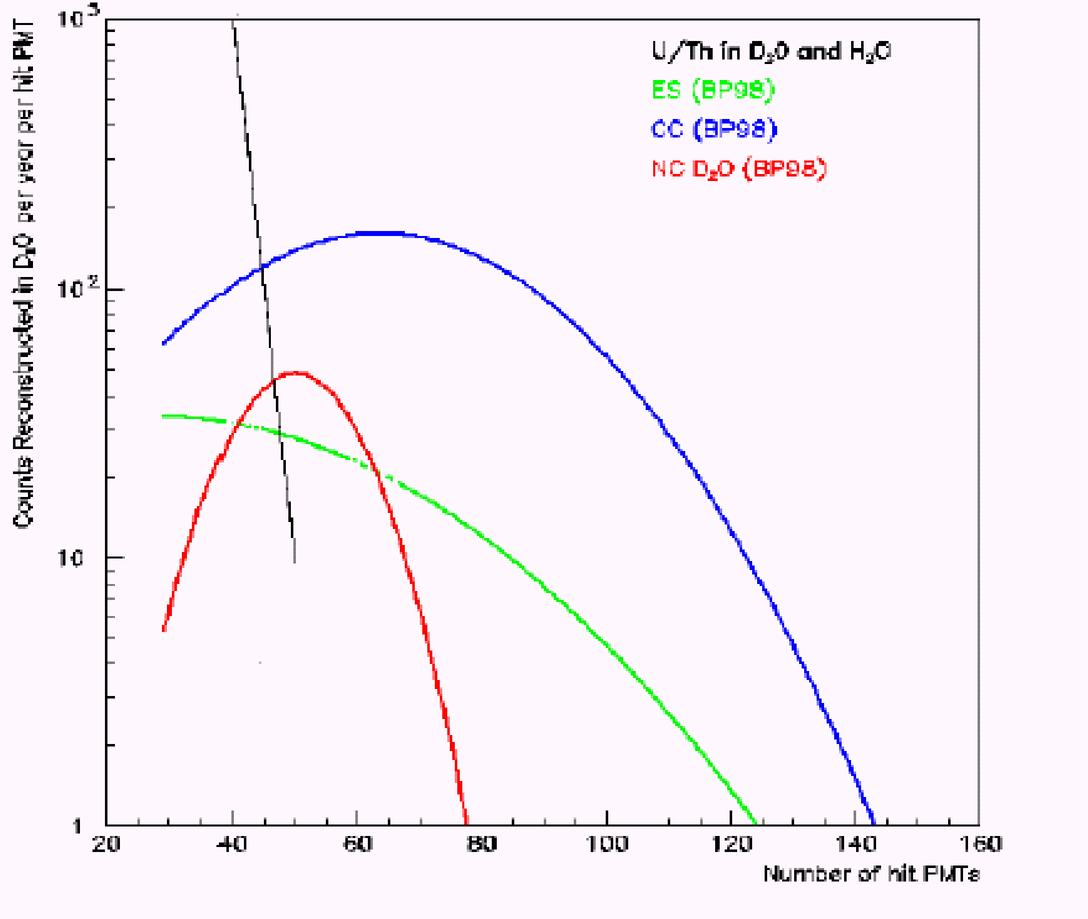
Advantages:

- ES excess points to Sun
- Can match energy regimes
- Super-K precision measurement

Signal/Background Spectra

Monte Carlo Predictions

(pure ^8B only)



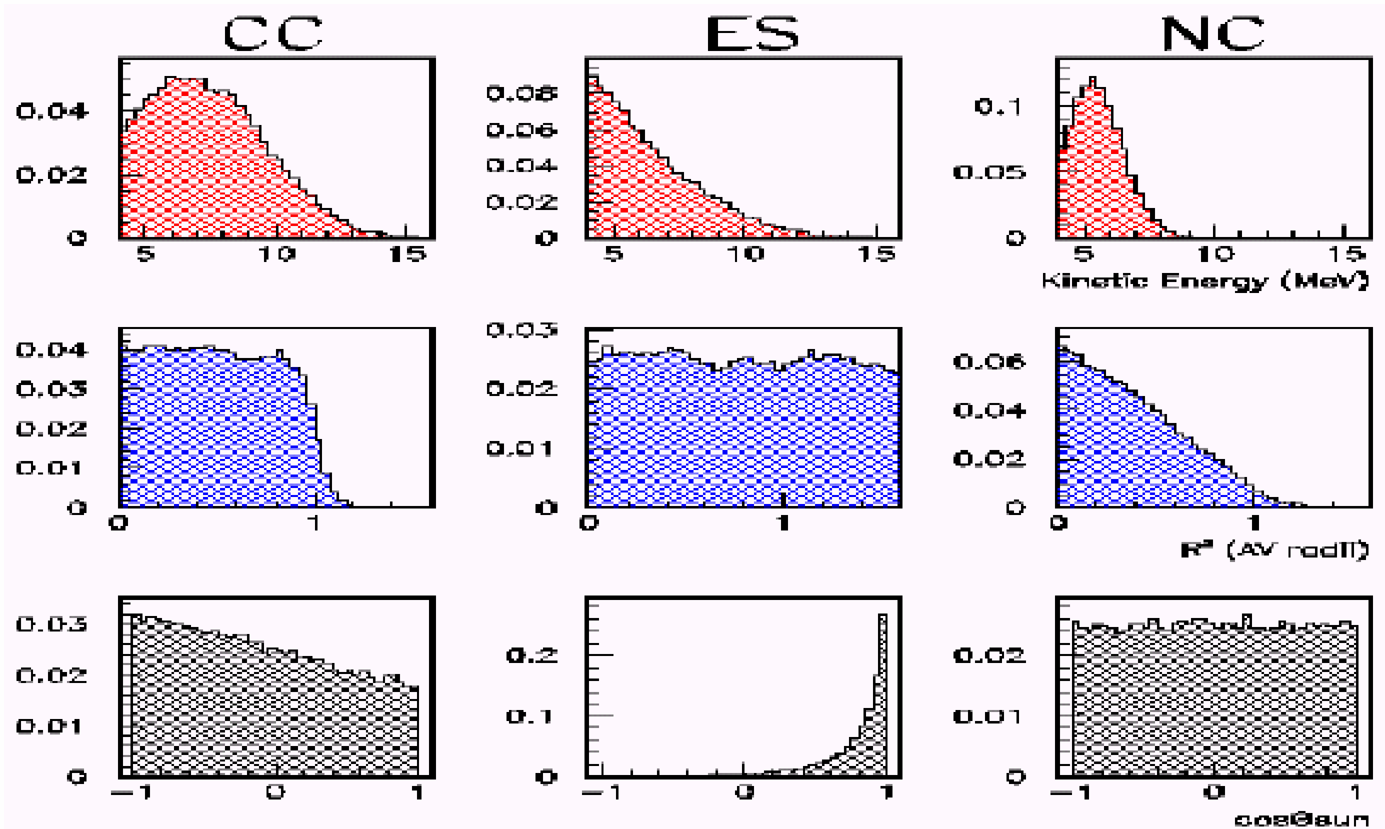
Extracting Signals

Can use derived observables (R^3, $\cos\theta_{sun}$, and E) to produce pdfs.

Energy
stribution

Radial
stribution
^{3}, R_{AV}=1)

Solar
Direction
stribution



Max. Likelihood fit for relative signal amplitudes

Signal extraction (units: 10^6 $cm^{-2}s^{-1}$)

$\Phi^{CC}_{SNO}(^8B) = 1.75 \pm 0.07 ^{+0.12}_{-0.11} \pm 0.05$ SNO

$\Phi^{ES}_{SNO}(^8B) = 2.39 \pm 0.34 ^{+0.16}_{-0.14}$ SNO

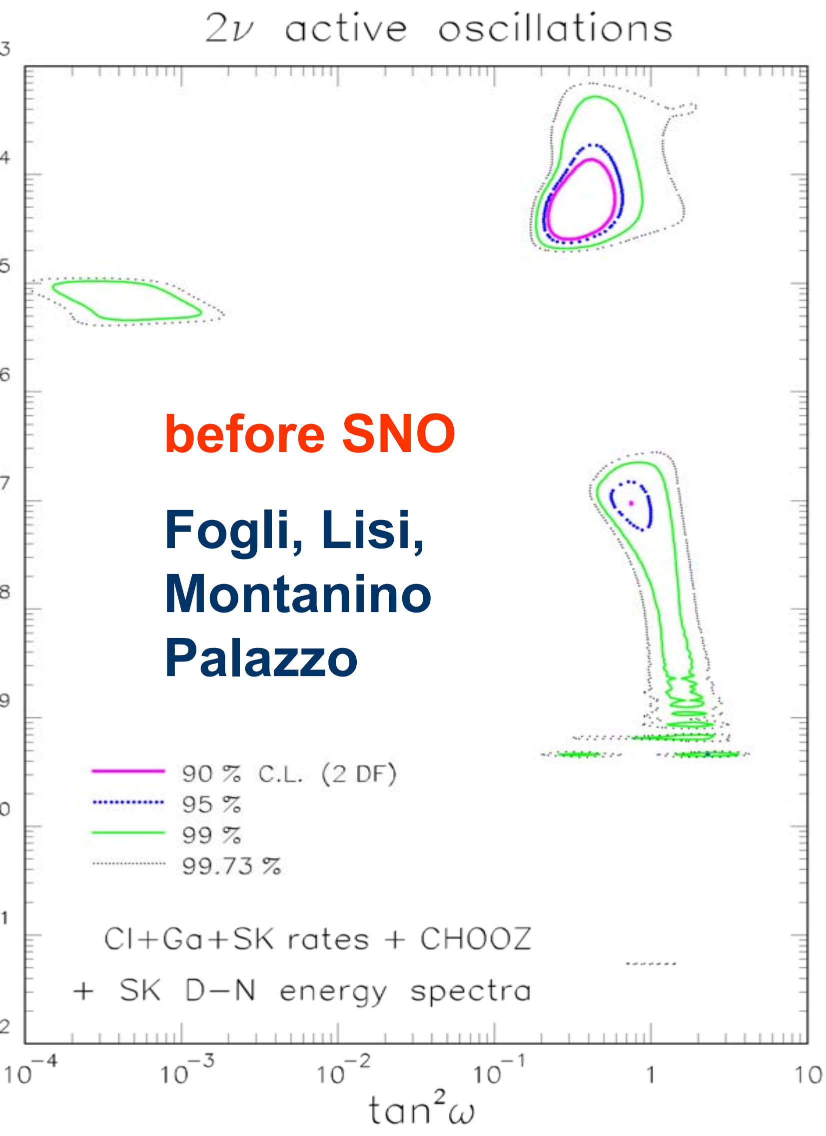
$\Phi^{ES}_{SNO} - \Phi^{CC}_{SNO} = 0.64 \pm 0.40$ — 1.6 σ (SNO)

$\Phi^{ES}_{SK}(^8B) = 2.32 \pm 0.03 ^{+0.08}_{-0.07}$ SuperK

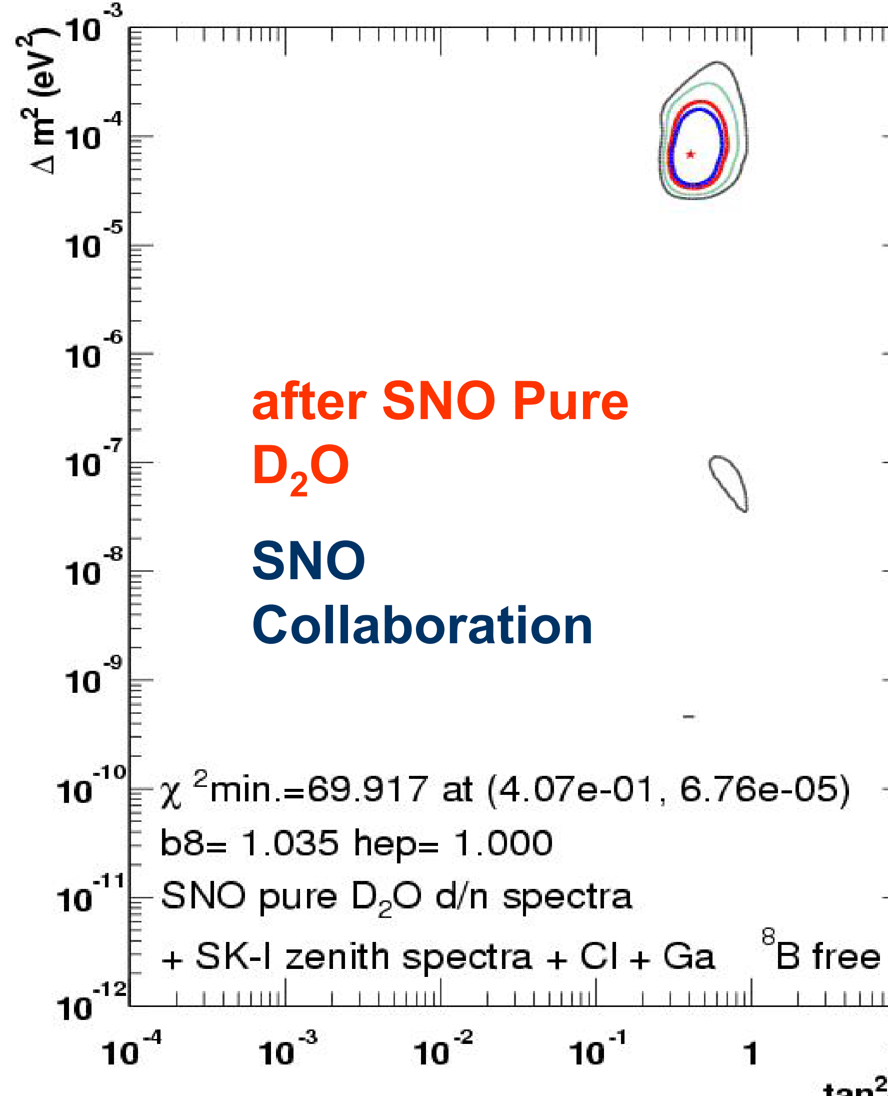
$\Phi^{ES}_{SK} - \Phi^{CC}_{SNO} = 0.57 \pm 0.17$ — 3.3 σ (SNO+SuperK)

Appearance in the solar flux of active neutrino $\neq \nu_e$
Pure $\nu_e \rightarrow \nu_{sterile}$ oscillation excluded at more than 3σ

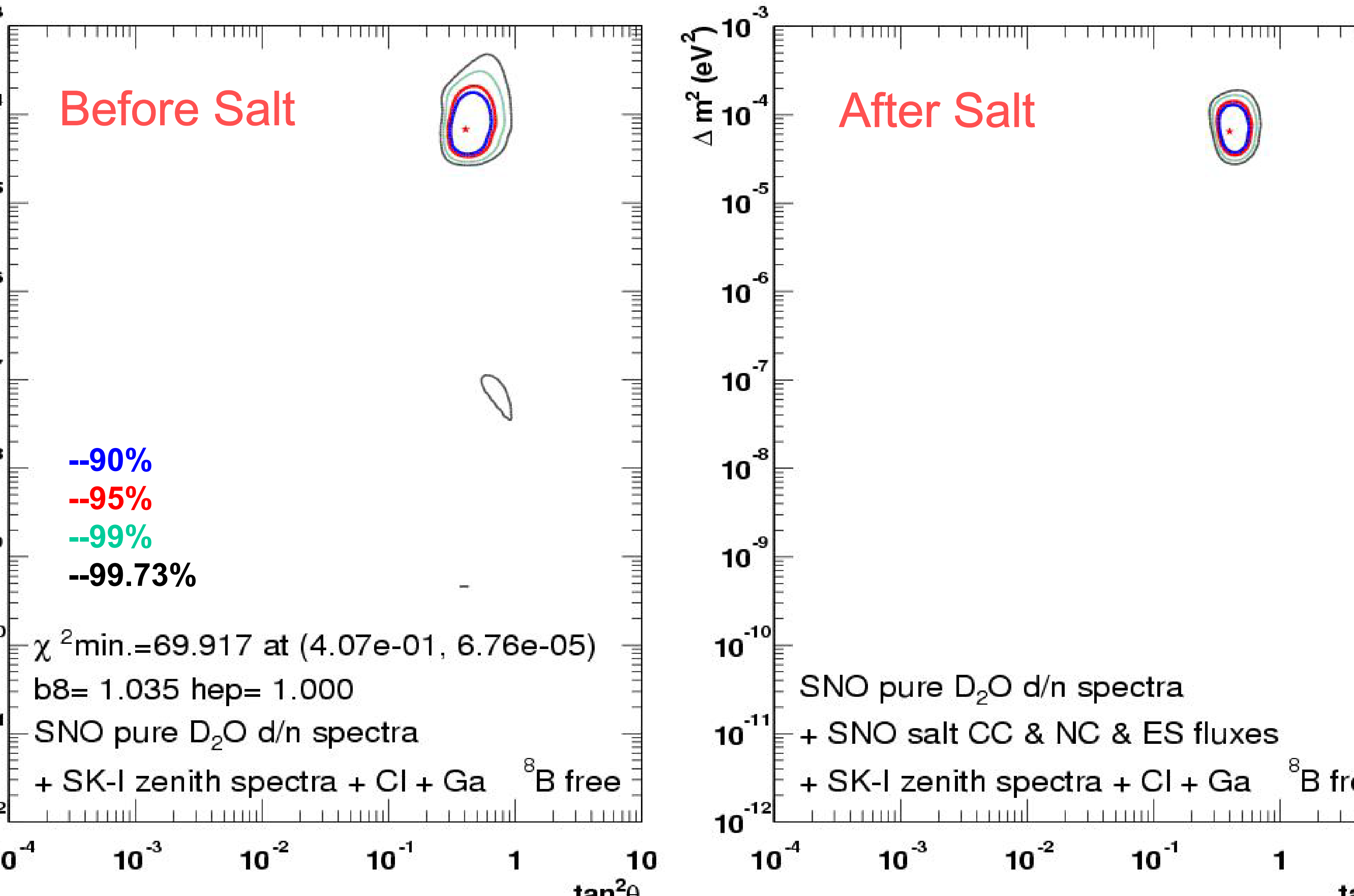
Oscillations Analysis: Before SNO



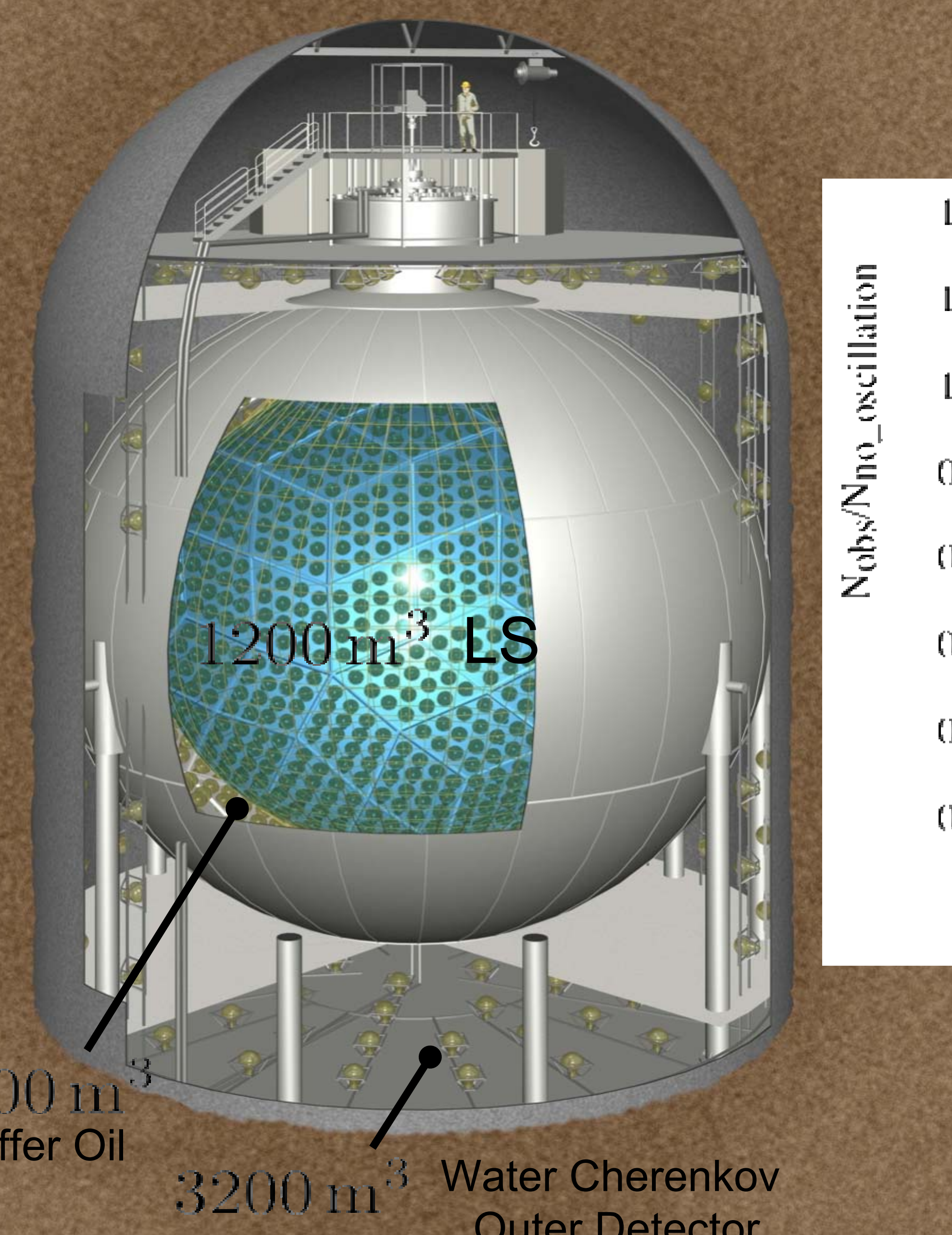
this figure updated and upgrad



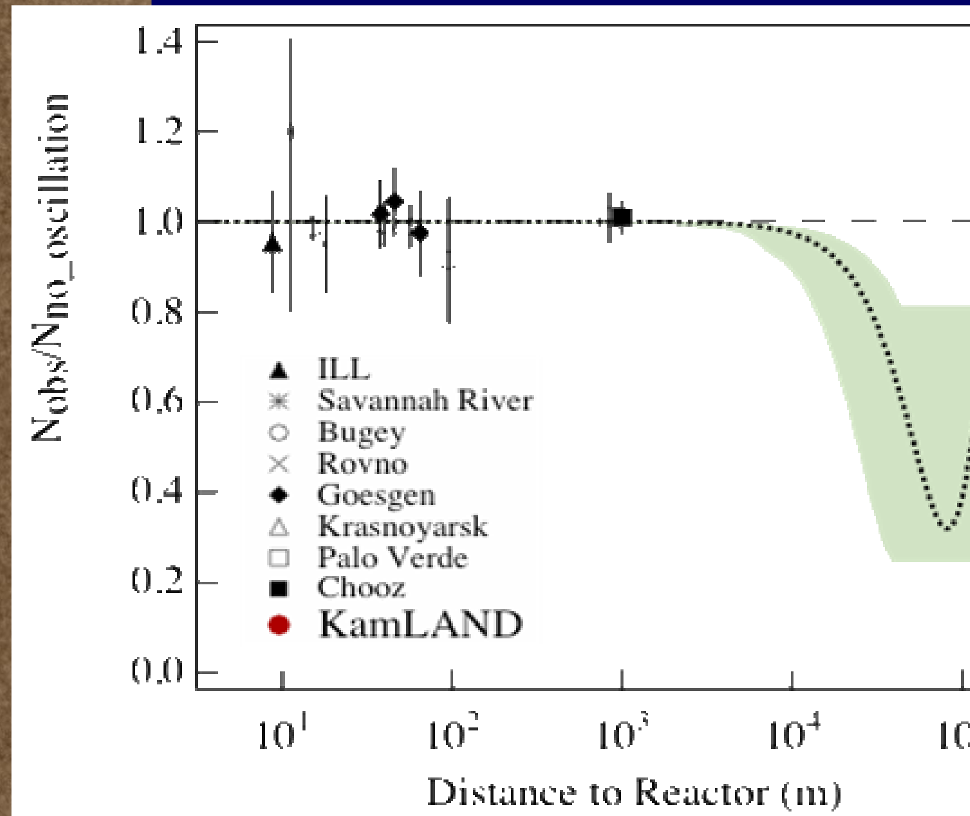
Oscillation Analysis: Global Solar



KamLAND



1200 m3 LS
00 m3
ffer Oil
3200 m3
Water Cherenkov
Outer Detector



Nobs/Nno_oscillation
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
ILL
Savannah River
Bugey
Rovno
Goesgen
Krasnoyarsk
Palo Verde
Chooz
KamLAND
10^1
10^2
10^3
10^4
Distance to Reactor (m)

1st result

Data Summary

from March 4 to October 6, 2002
-5.1 live days, 162 ton-year exposure

nalysis threshold 2.6 MeV

expected signal	86.8 ± 5.6
BG	1 ± 1
observed	54

Neutrino disappearance at 99.95% CL.

$= 0.611 \pm 0.085(\mathrm{stat}) \pm 0.041(\mathrm{syst})$

amLAND collaboration, Phys.Rev.Lett.90(2003)021802

2 nd result

Data Summary

from 9 Mar 2002 to 11 Jan 2004
515.1 live days, 766.3 ton-year exposure
×4.7 exposure (×3.55 live time, ×1.33 fiducia

expected signal	365.2 ± 23.7
BG	7.5 ± 1.3
observed	258

Neutrino disappearance at 99.995% CL

$R = 0.686 \pm 0.044(\mathrm{stat}) \pm 0.045(\mathrm{sy}$

$R = 0.582 \pm 0.069 \pm 0.039$

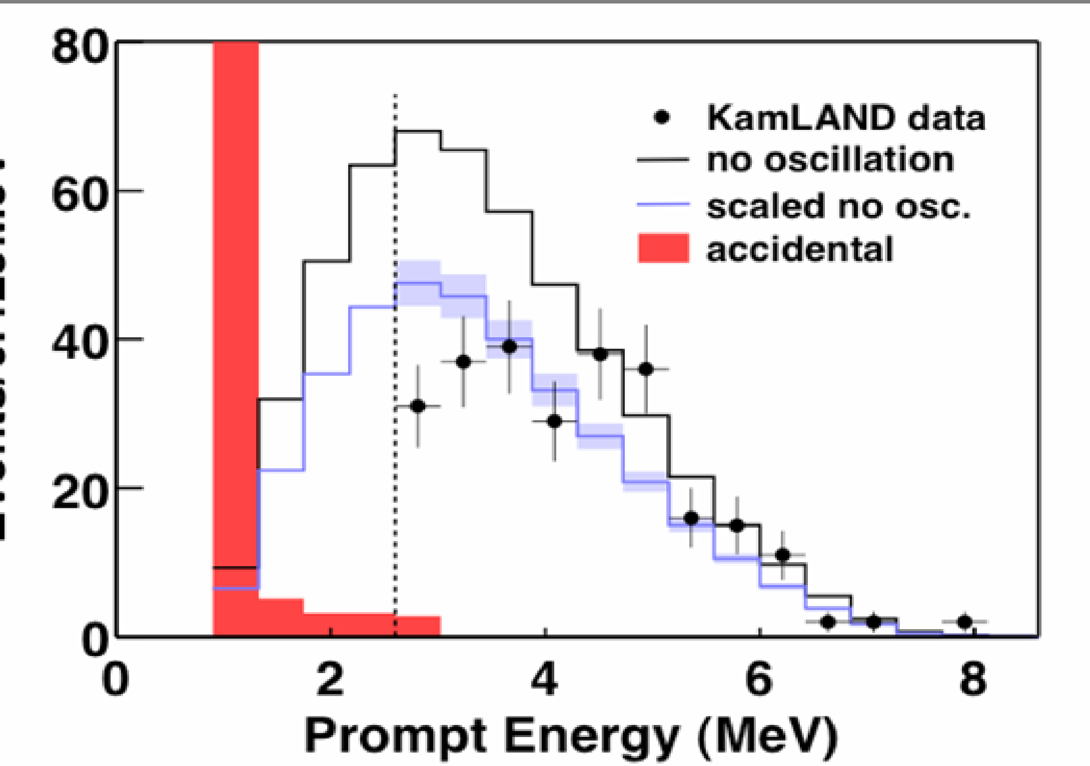
for Mar to Oct 2002

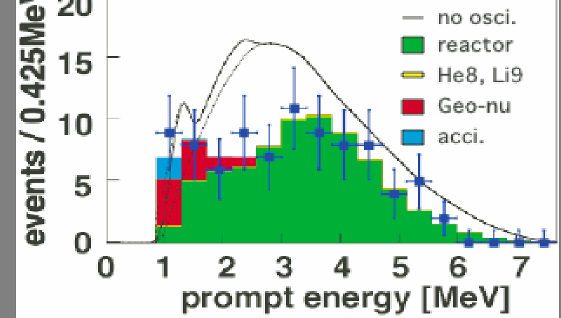
is consistent with first results

KamLAND collaboration, hep-ex/0406035

Evidence for reactor neutrino disappearance

Energy Spectrum





hypothesis
no oscillation

$$\chi^2/\mathrm{dof} = 43.4/19$$

for 20 equal probability bi

goodness of fit (MC)
0.1%

spectral distortion at 99.9% CL

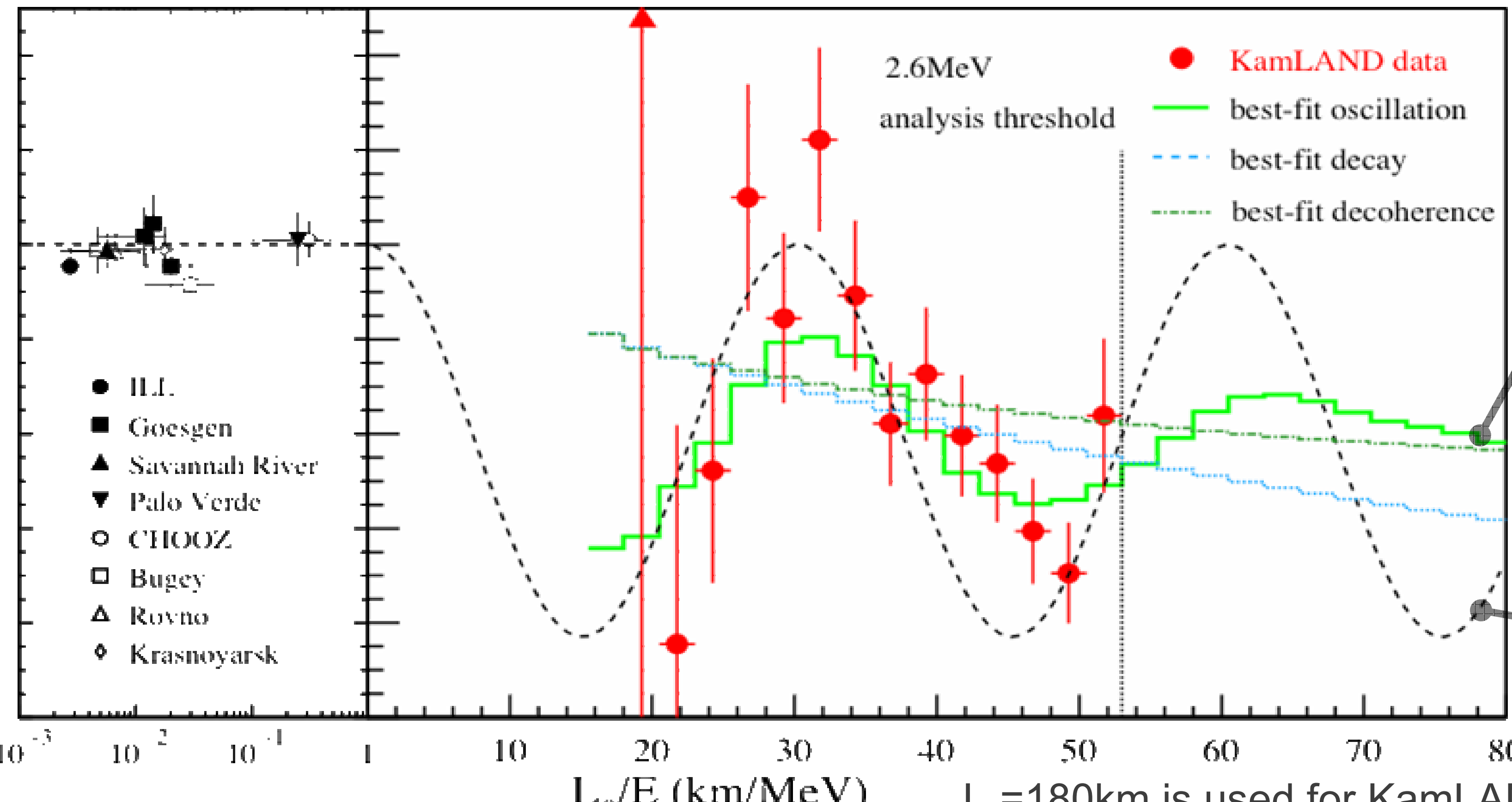
rate + shape 99.99996% CL

L/E dependence

oscillation $P_{ee} = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2}{4}\frac{L}{E})$

decay $P_{ee} = (\cos^2\theta + \sin^2\theta \exp(-\frac{m_2}{2\tau}\frac{L}{E}))^2$ V.D.Bager et al.,PRL82,2

decoherence $P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta(1 - \exp(-\gamma\frac{L}{E}))$ E.Lisi et al.,PRL85,1166(

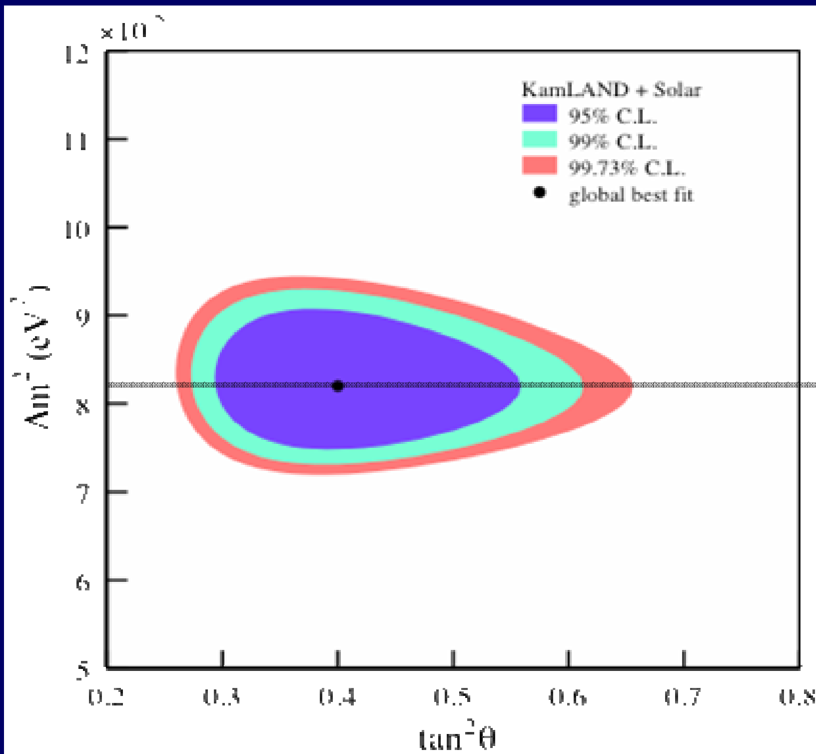


actual re
distribut
conside

hypoth
single r

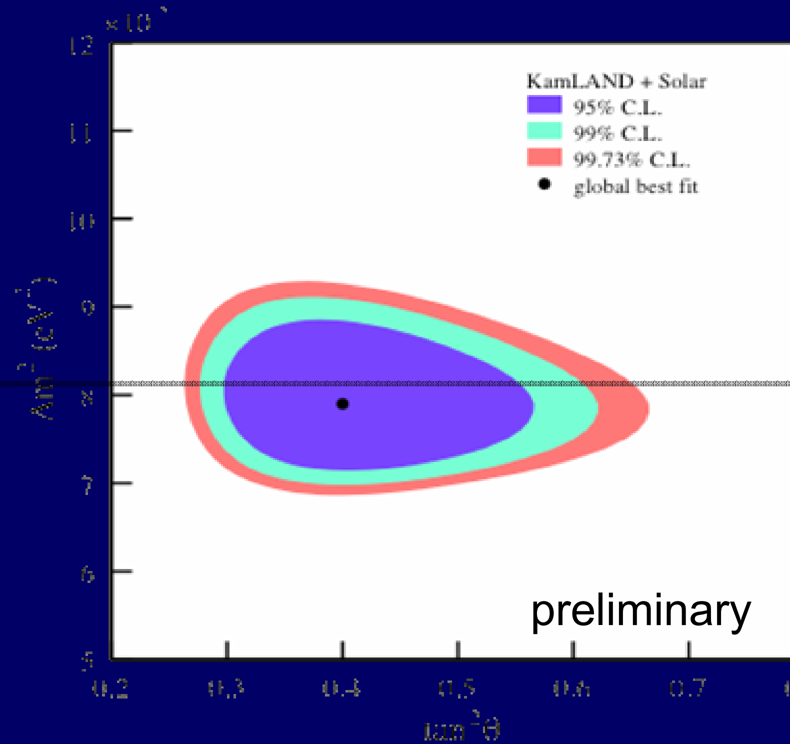
L =180km is used for KamLAND

Solar + KamLAND global analysis



$$\Delta m^2 = 8.2^{+0.6}_{-0.5} \times 10^{-5}\,\mathrm{eV}^2$$

$$\tan^2\theta = 0.40^{+0.09}_{-0.07}$$

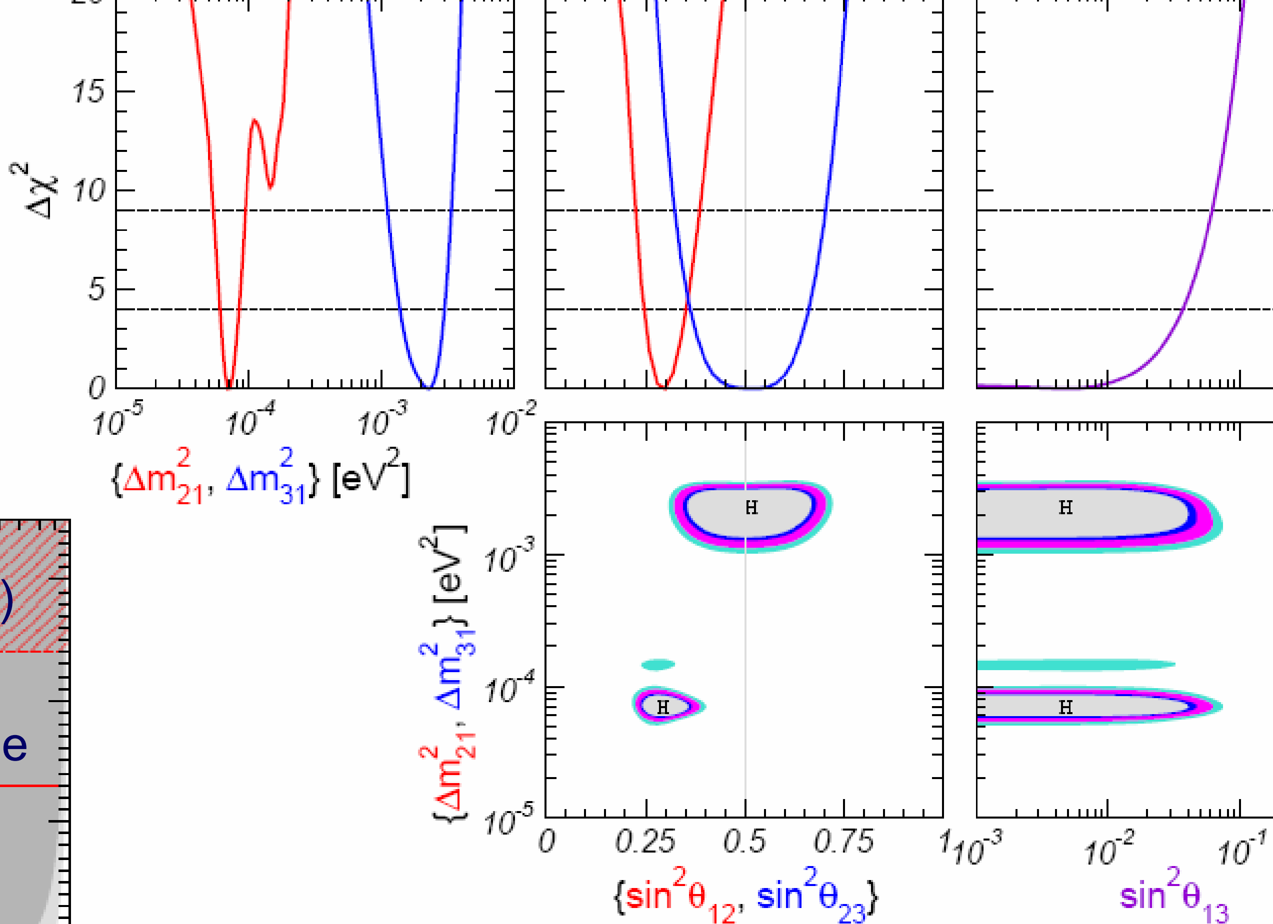


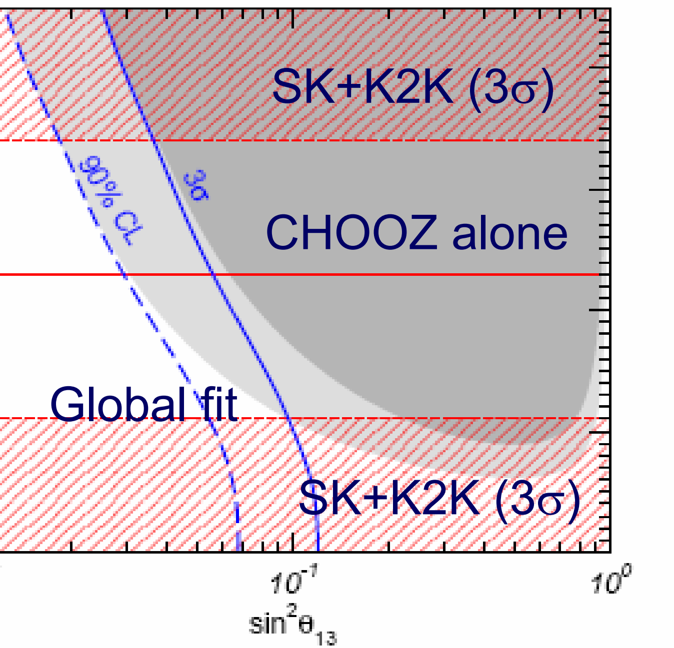
Unnoticed BG slightly changes the res

Global fit (Maltoni et al.)

ur present knowledge of
e oscillation parameters

(all data included)



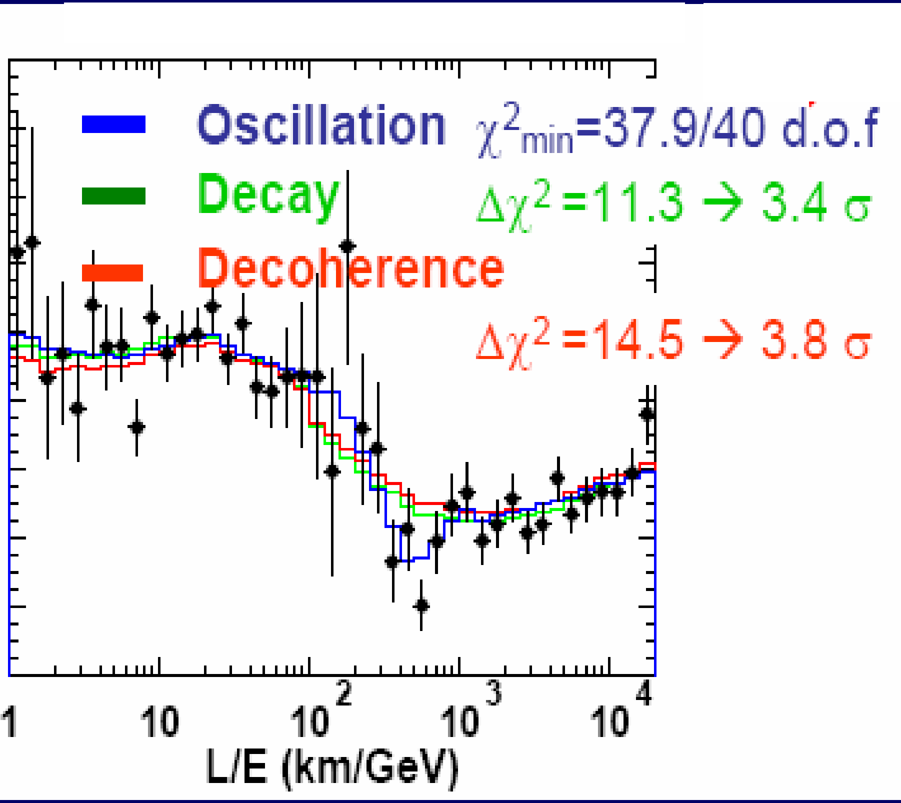


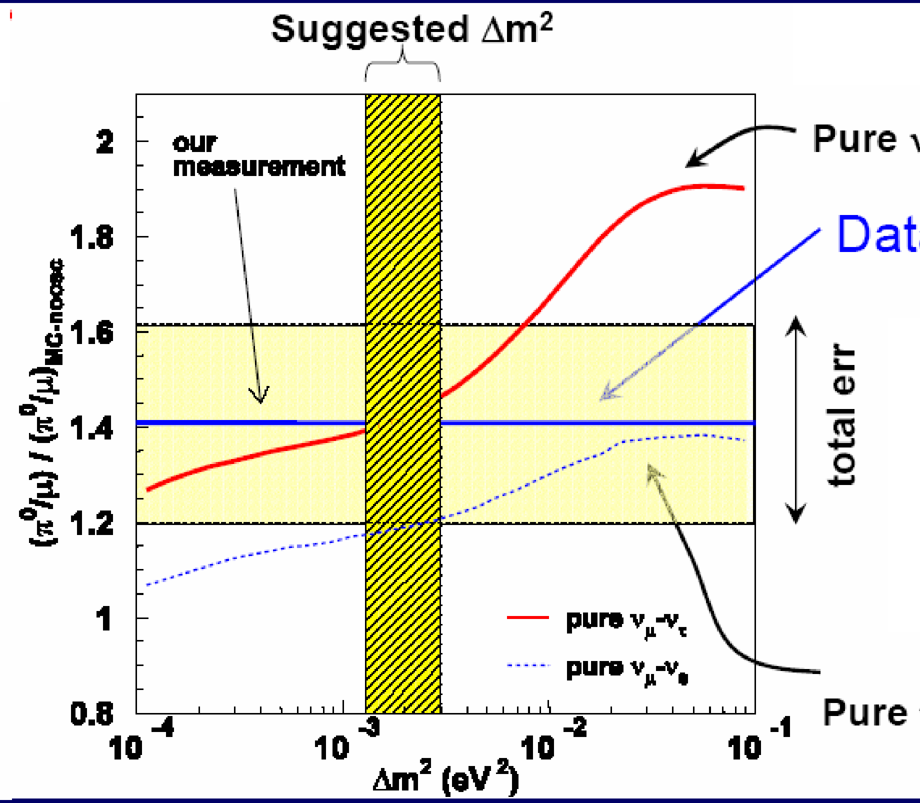
parameter	best fit	2σ	3σ	
Δm^2_{21} [10^{-5}eV^2]	6.9	6.1–8.4	5.4–9.4	2.
Δm^2_{31} [10^{-3}eV^2]	2.3	1.4–3.0	1.1–3.4	0.6
$\sin^2\theta_{12}$	0.30	0.25–0.35	0.23–0.39	0.16
$\sin^2\theta_{23}$	0.52	0.36–0.66	0.32–0.70	0.26
$\sin^2\theta_{13}$	0.005	≤ 0.037	≤ 0.061	$\leq$

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

$\theta_{13} < 11°$

Interesting results from SK with atmospheric neutrinos: L/E distribution (for selected high-resolution events) and NC/CC ratio (τ or sterile neutrino ?)





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

ospheric neutrino deficit is due to ν_μ → ν_τ oscillations (not to generic conversi

oals of planned and future neutrino beam experiments:

bserve ν_τ appearance → …find the body after the murder…

s there (some) room for a sterile neutrino? → MiniBoone and ν_μ disappearanc

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 $\pi/4$?

ind the value of θ_{13} from P(ν_μ-ν_e) → benchmark 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..

focus on accelerator experiments

eutrino mixing matrix and general 3 neutrino oscillation probabilit

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

$$\begin{aligned} P(\nu_\ell \to \nu_{\ell'}) &= |\sum_i U_{\ell i} U^*_{\ell' i} e^{-i(m_i^2/2E)L}|^2 \\ &= \sum_i |U_{\ell i} U^*_{\ell' i}|^2 + \Re \sum_i \sum_{j \neq i} U_{\ell i} U^*_{\ell' i} U^*_{\ell j} U_{\ell' j} e^{i\frac{|m_i^2 - m_j^2| L}{2E}} \end{aligned}$$

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

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

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

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

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

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

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

θ_{13} **is the link betw solar and atmosphe oscillations**

ere

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$
$$A = \sqrt{2}G_F n_e$$
$$B_\pm = |A \pm \Delta_{13}|$$
$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

d the $\pm$ signifies neutrinos or antineutrinos

$\nu_\mu \rightarrow \nu_e$ oscillations:

Solar part: small Δm^2, large mixing

Sub-leading: large Δm^2, small mixing (?

→ The two effects can compete

In vacuum, at leading order:

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

vacuum and in absence of δ-phase:

$$\left(\nu_\mu \rightarrow \nu_e\right) \approx \underbrace{\cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}L}{2}\right)^2}_{solar\ \ part} + \underbrace{\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta_{13}L}{2}\right.}_{atmospheric\ \ part}$$

ative importance:

$$_{/solar} \equiv \frac{\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta_{13}L}{2}\right)}{\cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}L}{2}\right)^2} \approx \frac{\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta_{13}L}{2}\right)}{\sin^2 2\theta_{12}\left(\frac{\Delta_{12}L}{2}\right)^2} \approx \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{12}}\left(\frac{\Delta}{\Delta}\right.$$

$$E_\nu \rightarrow \infty$$

umerically:

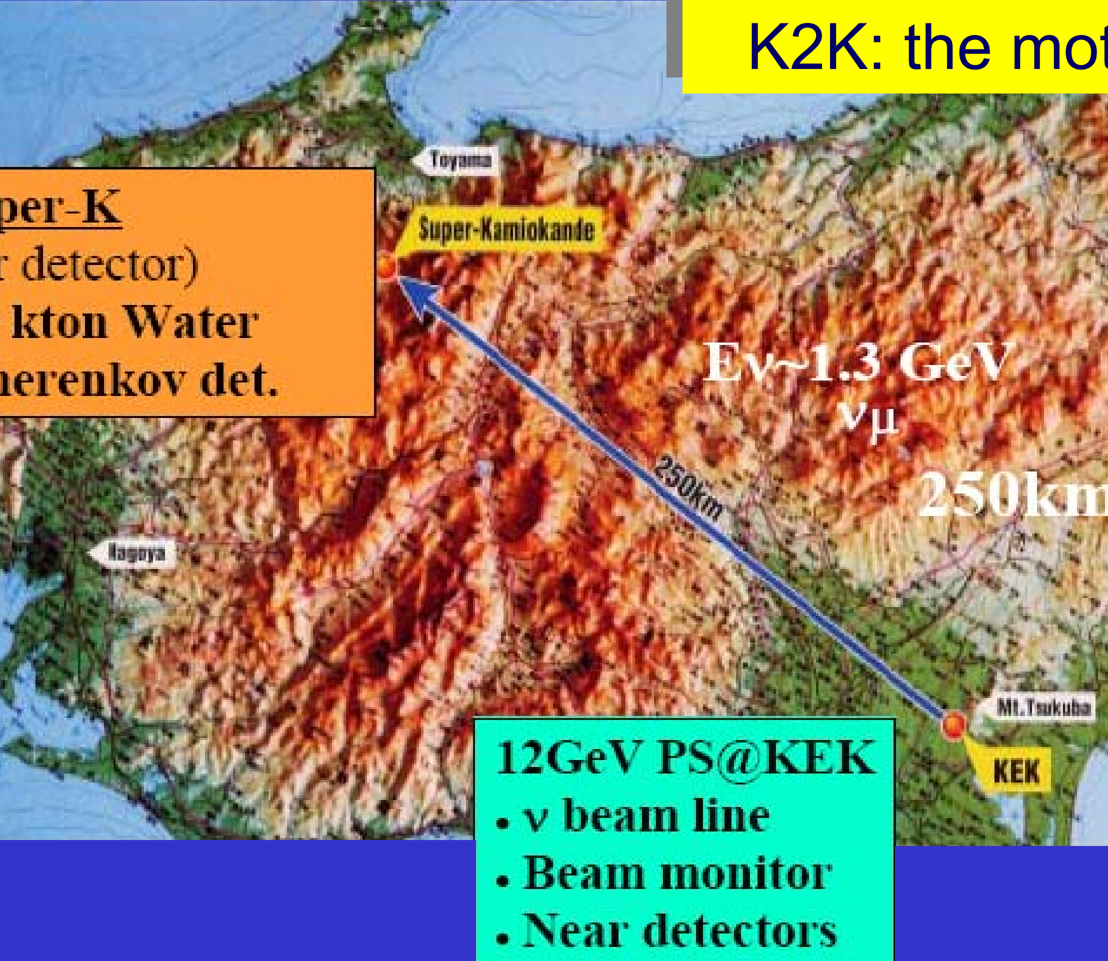
$$\frac{1}{\mathrm{n}^2 2\theta_{12}}\left(\frac{\Delta_{13}}{\Delta_{12}}\right)^2 \approx 10^3$$

Solar > atmospheric for $\sin^2 2\theta_{13} <\approx 10$

For $\sin^2 2\theta_{13} <$ 10^{-3}, correlations with solar parameters are important to determine sensitivity. NF down to 10^{-5} ??

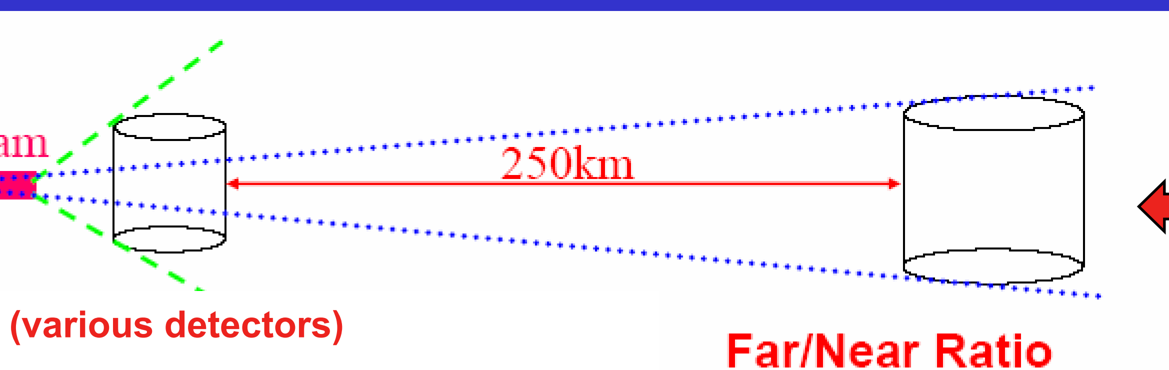
Work in progress…

K2K: the mother of all LBL experiment

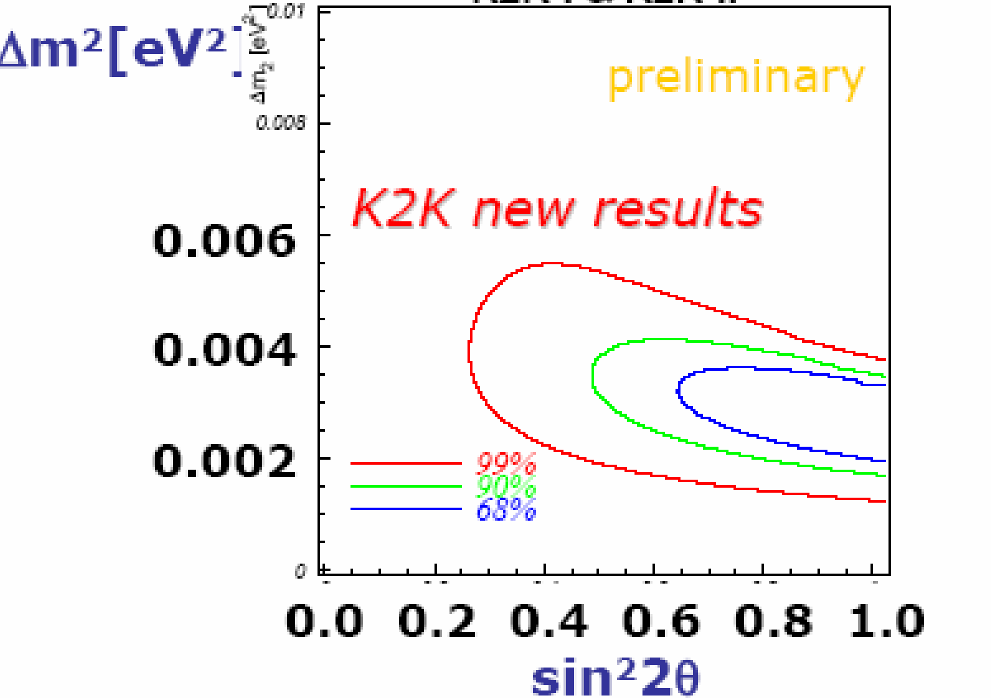


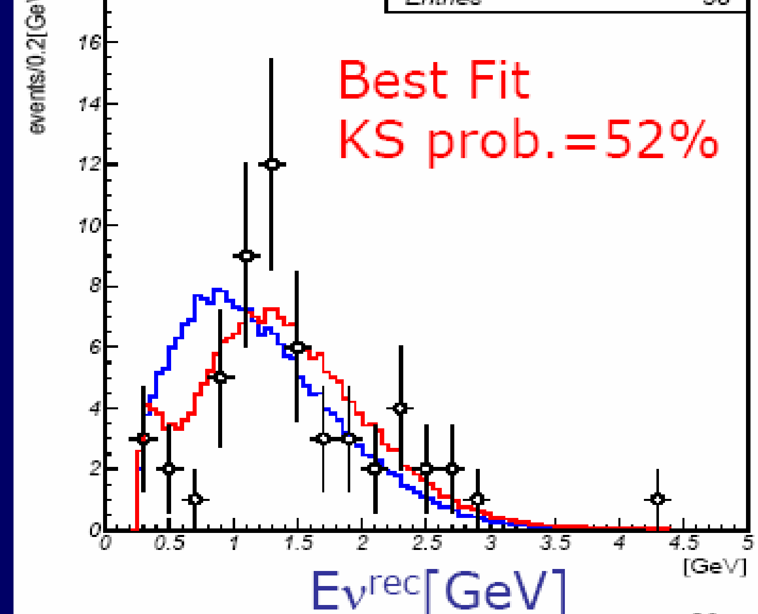
ν_μ **disappearance experiment to probe the SK atmospheric neutrino result.**

Analogous case to Kamland vs solar neutrino experiments



near/far detectors compariso event rate and energy spect shape





K2K latest results:

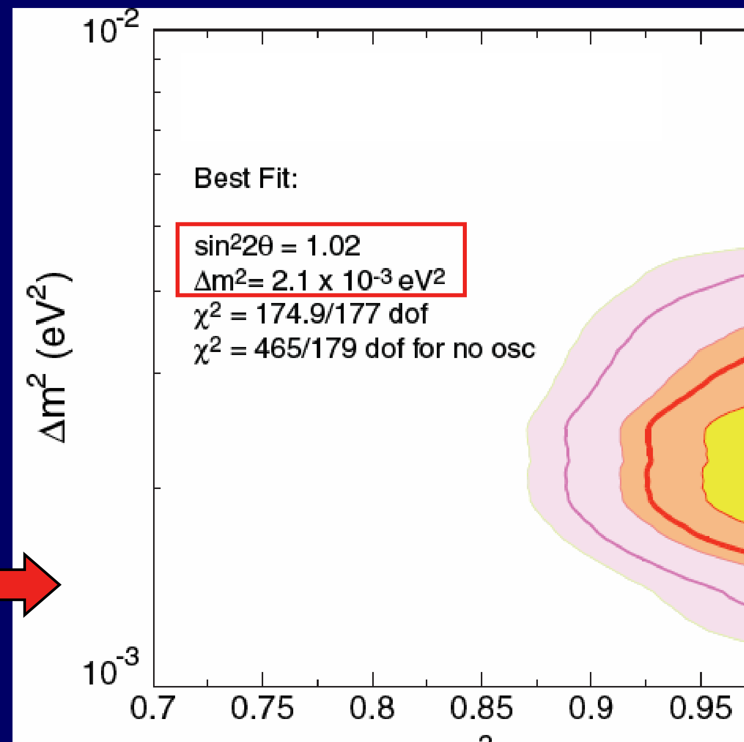
7 < Δm^2 < 3.5 eV² for $\sin^2 2\theta = 1$ (90% CL)

(ν_μ disappearance plus shape distortion)

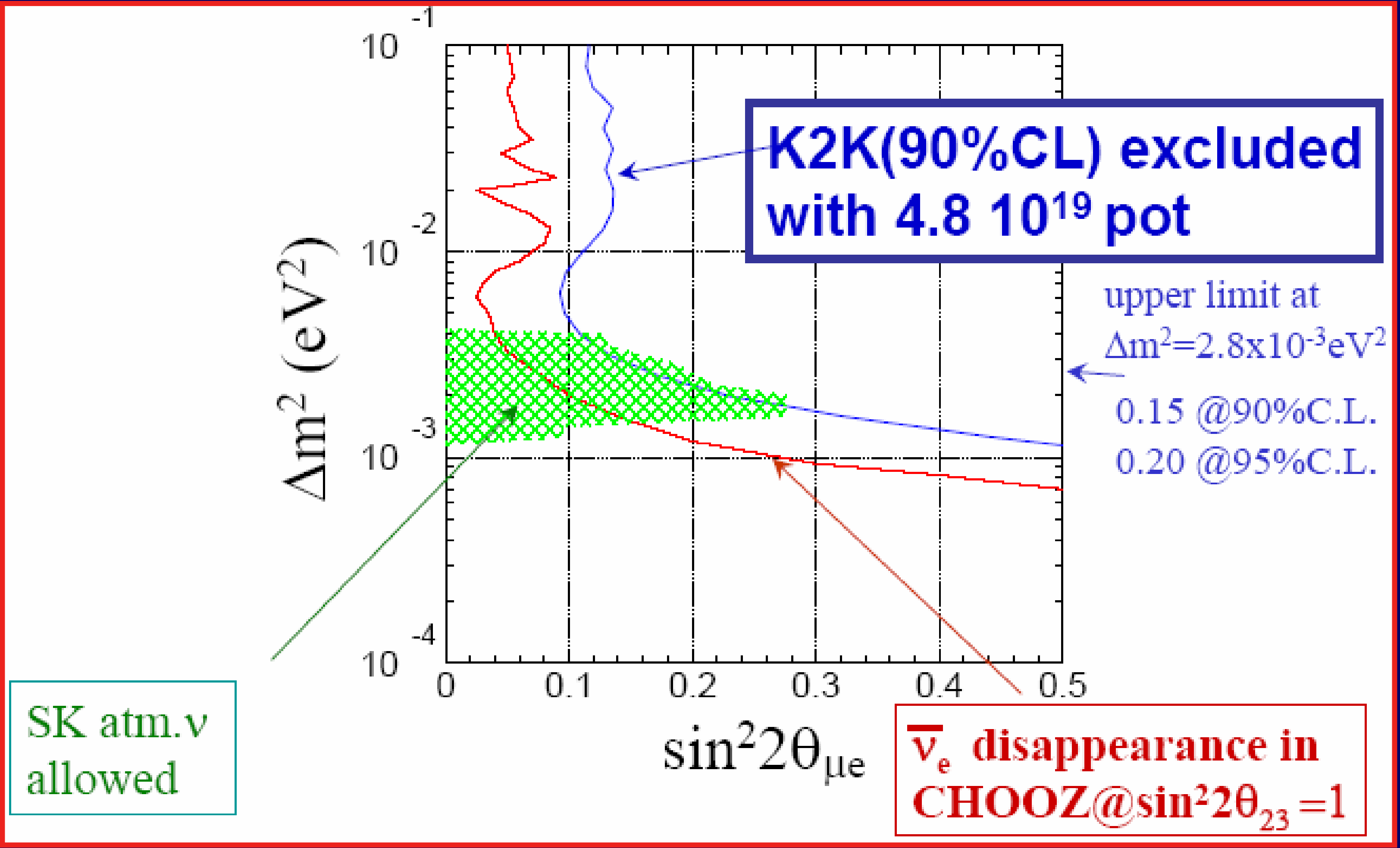
oscillation hypothesis confirmed at 3.9 σ

K2K confirms SK:

< Δm^2 < 3.4 eV² for $\sin^2 2\theta > 0.93$ (90% CL)



K2K looking for electron appearance

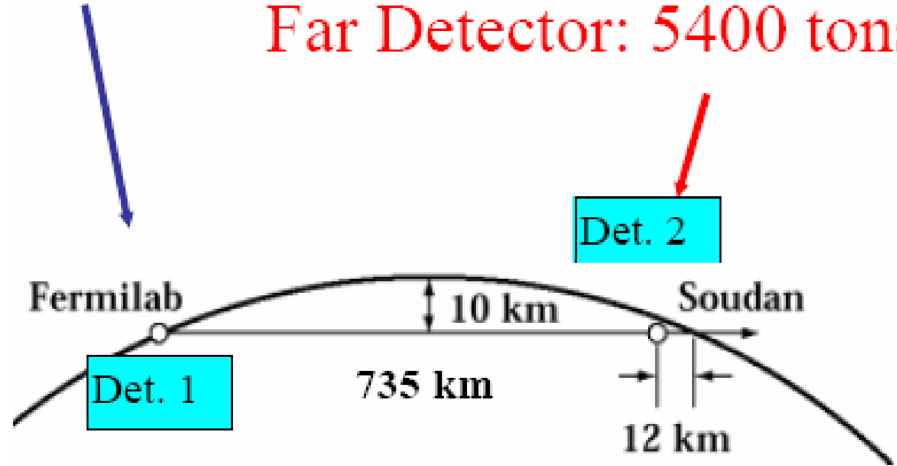


Next to come on duty: MINOS in the NuMi neutrino beam

Start 20

Near Detector: 980 tons

Far Detector: 5400 tons



Magnetized steel/scintillator calorimeter

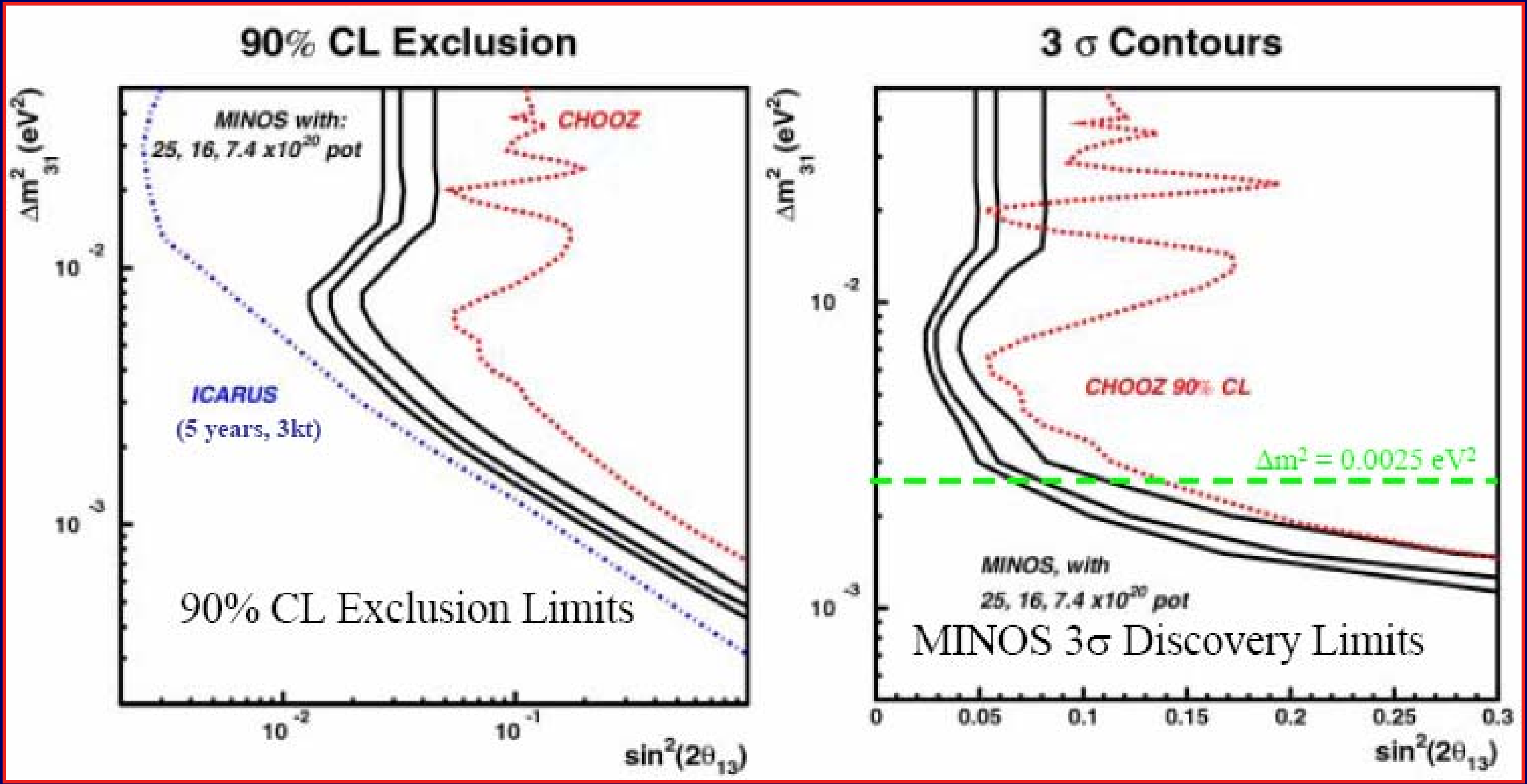
w E neutrinos (few GeV): ν_μ disappearance experiment

x10^{20} pot/year → 2500 ν_μ CC/year

ompare Det1-Det2 response vs E → in 2-6 years sensitivity to Δm^2_{atm}

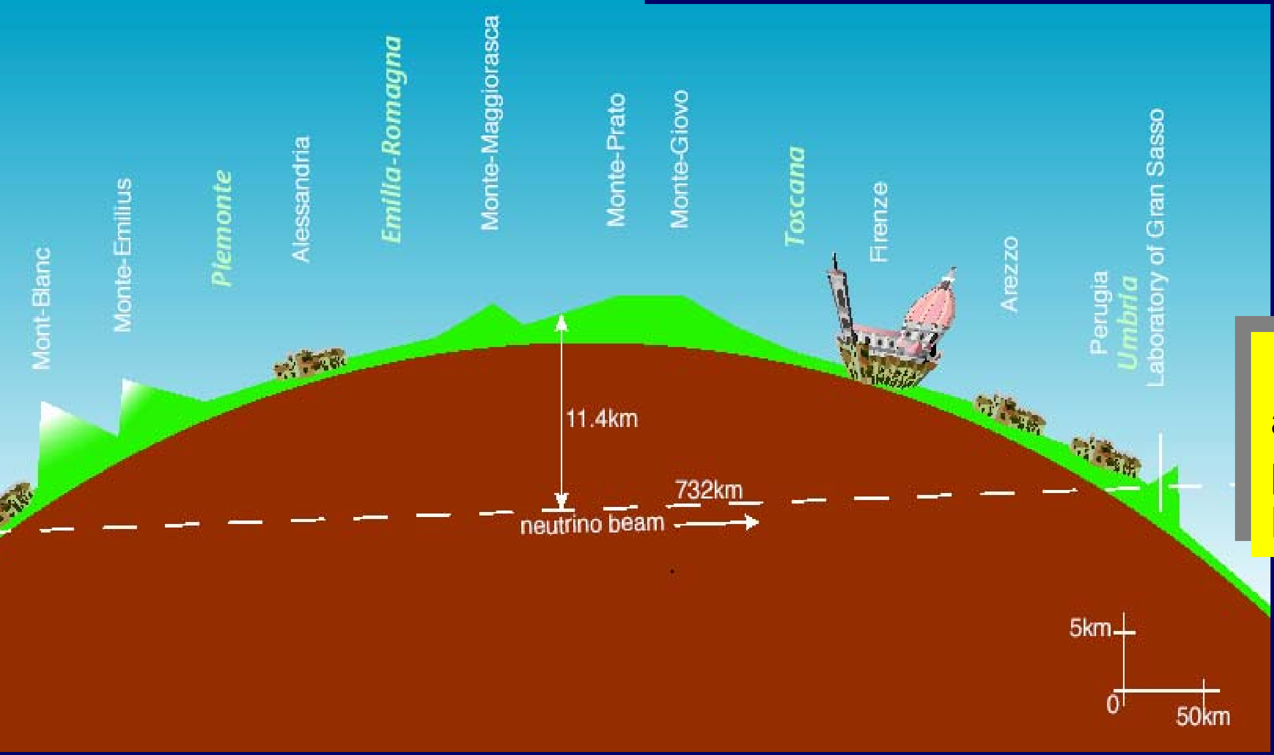
ain goal: reduce the errors on Δm^2_{23} and $\sin^2 2\theta_{23}$ as needed for $\sin^2 2\theta_{13}$ measurement

electron appearance in MINOS



In 4 years running (~2010) MINOS could improve the CHOOZ limit on $\sin^2 2\theta_{13}$ from ~0.14 to ~0.06, the 3σ "evidence" up to ~0.085

τ appearance at LNGS in the CNGS be



Start 20

Important investment: think about experiments beyond present generation ?
Low E or off-axis experiment

- High energy beam: <E> about 20 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
- construction well advanced: on schedule.
- Two experiments at LNGS: OPERA and ICARUS

OPERA experiment at LNGS: rebirth of the emulsion technique

tector: 1800 ton emulsion/lead bricks (ECC nique) complemented by tracking scintillator es and two muon spectrometers

ustrial emulsion production and handling

ed huge scanning power/speed: > tens of matic microscope running in parallel 0 cm^2/hour (advances of the technique)

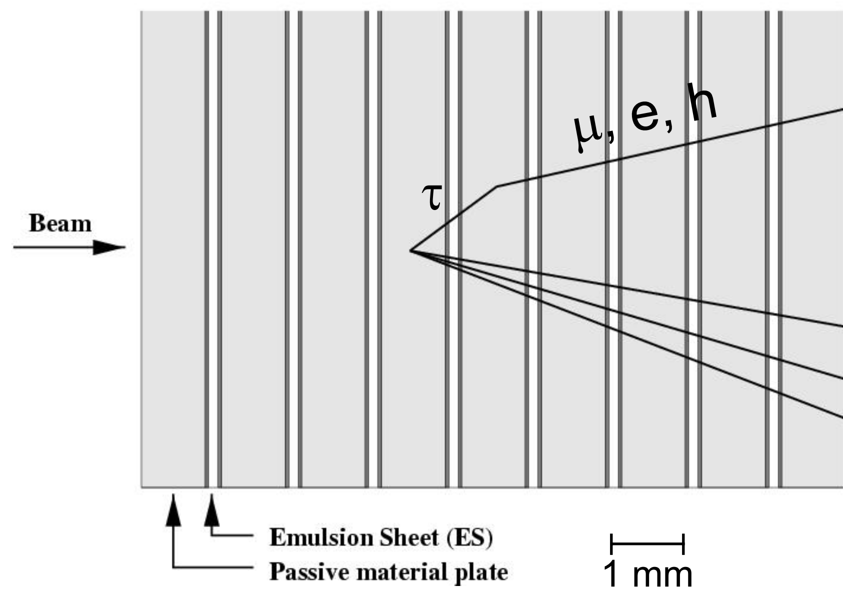
ecialized, single task experiment

v BG: <1 event (τ track reconstruction)

v statistics: about 10 events/5 years at inal CNGS intensity @ SK parameter values: istics goes like $(\Delta m^2)^2$

n at beam intensity increase

stallation in progress



Measure θ_{13}

Simple considerations

→ ν_e oscillation as a tool to measure θ_{13} with accelerator neutrino experiments.

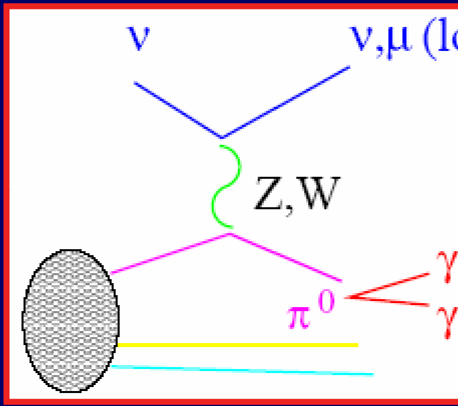
ure 'Super-CHOOZ-like' reactor experiments are difficult (and not covered here).
sting or planned atmospheric neutrino detectors can be limited by statistics.

nall effect (< 5% from CHOOZ)

ompt ν_e contamination at % level (accelerator neutrino beams)

ain BG: $\pi°$ production in NC and CC interactions →

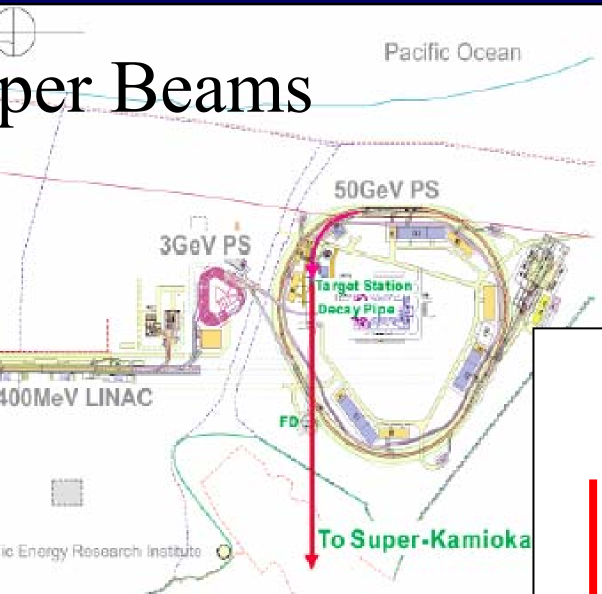
lditional BG: low energy muons and pions can fake electrons



→ ν_μ oscillations can solve most of the problems but hard to make ν_e beams
it for a next generation facilities)

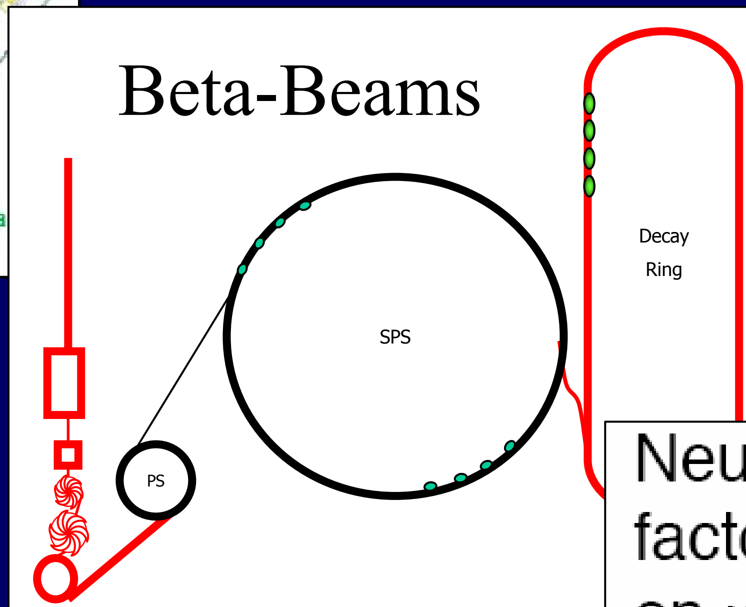
any case high intensity is a must !

Need high intensity: future neutrino faciliti



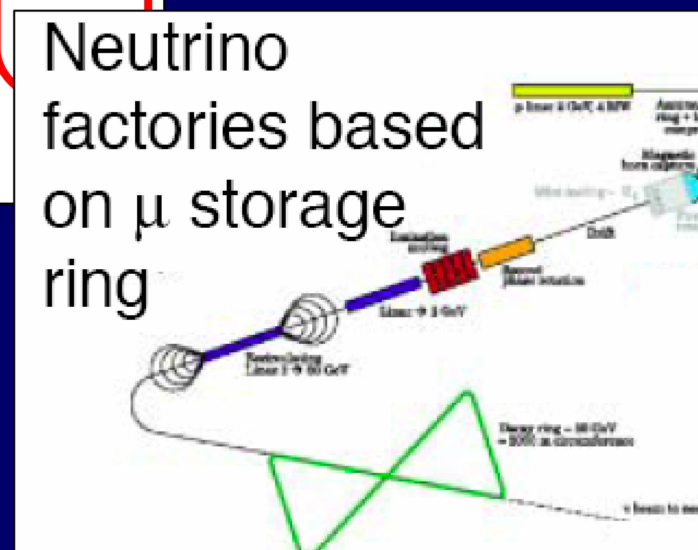
$$\pi^{\pm} \to \mu^{\pm} \overset{(-)}{\nu}_{\mu}$$

Select focusing sign



$$^{Z}A \to {}^{Z\mp1}A \ \beta^{\pm}$$

Select ion

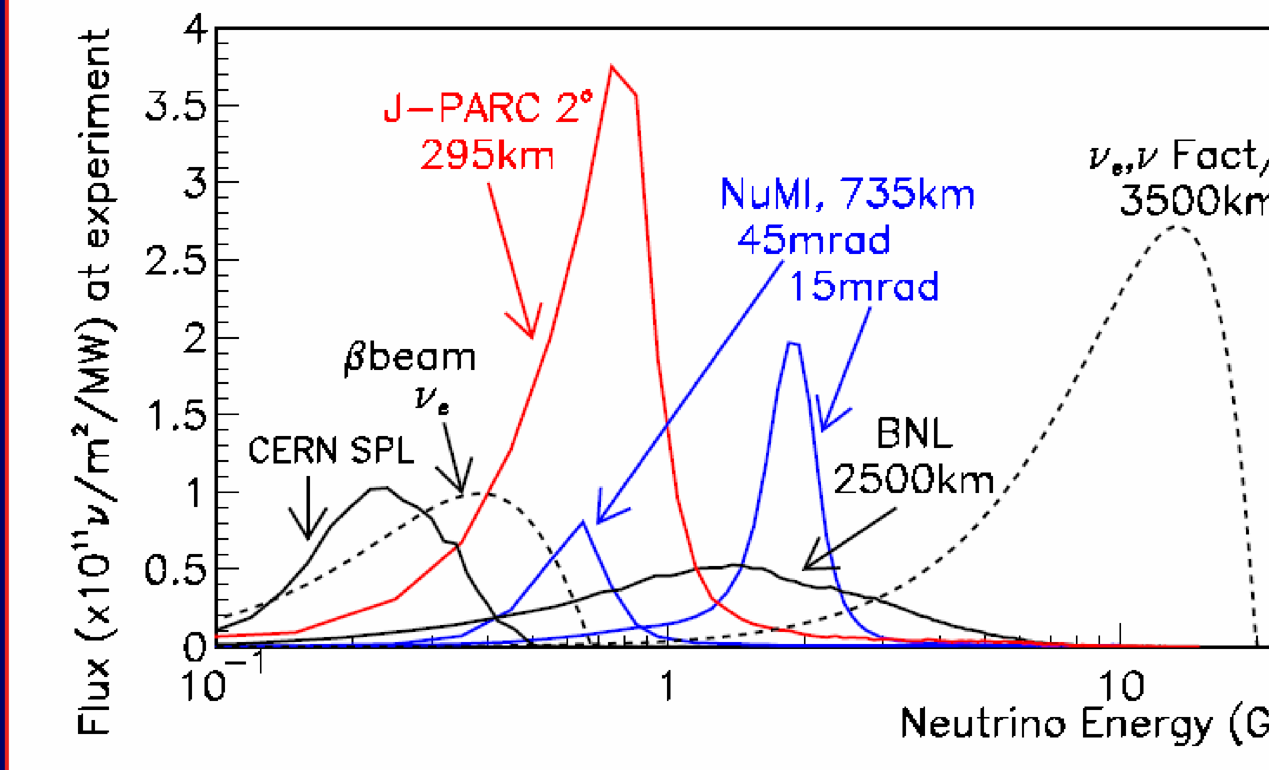


$$\mu^{-} \to e^{-}\bar{\nu}_{e}\nu_{\mu}$$

$$\mu^{+} \to e^{+}\nu_{e}\bar{\nu}_{\mu}$$

Select ring sign

ure neutrino beams



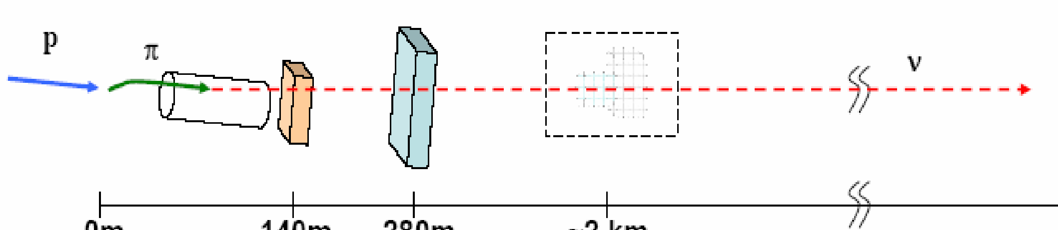
standing goals

ysics	Value of $\sin^2 2\theta_{13}$ $> 4 \times 10^{-2}$	$> 1 \times 10^{-2}$	$> 10^{-3}$	$> 10^{-4}$
ing $\theta_{13} \neq 0$	MINOS CNGS	Conventional Superbeams Phase I	Conventional Superbeams Phase II	ν Factory $L \geq 3500$ km
ss erarchy	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
idence for -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 Tokai to SK

Start

- 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 $\pi°$ BG
- SK plus three near detectors

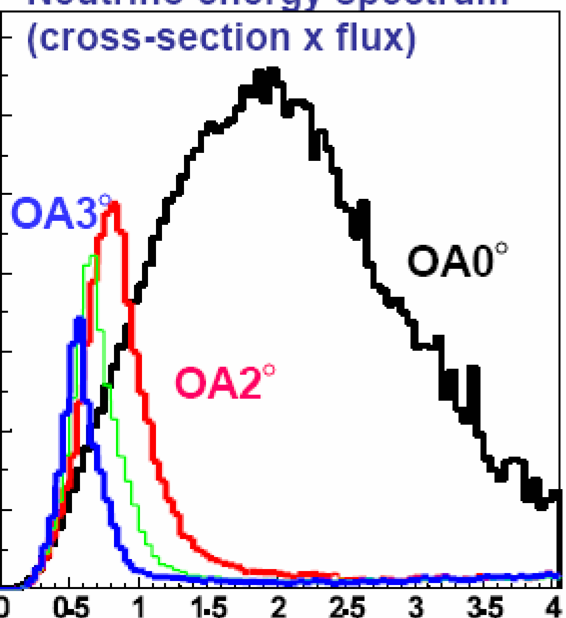


μ monitor (beam direction and intensity)

ν energy spectrum and intensity

Same spectrum as S
BG measurement

Neutrino energy spectrum (cross-section x flux)

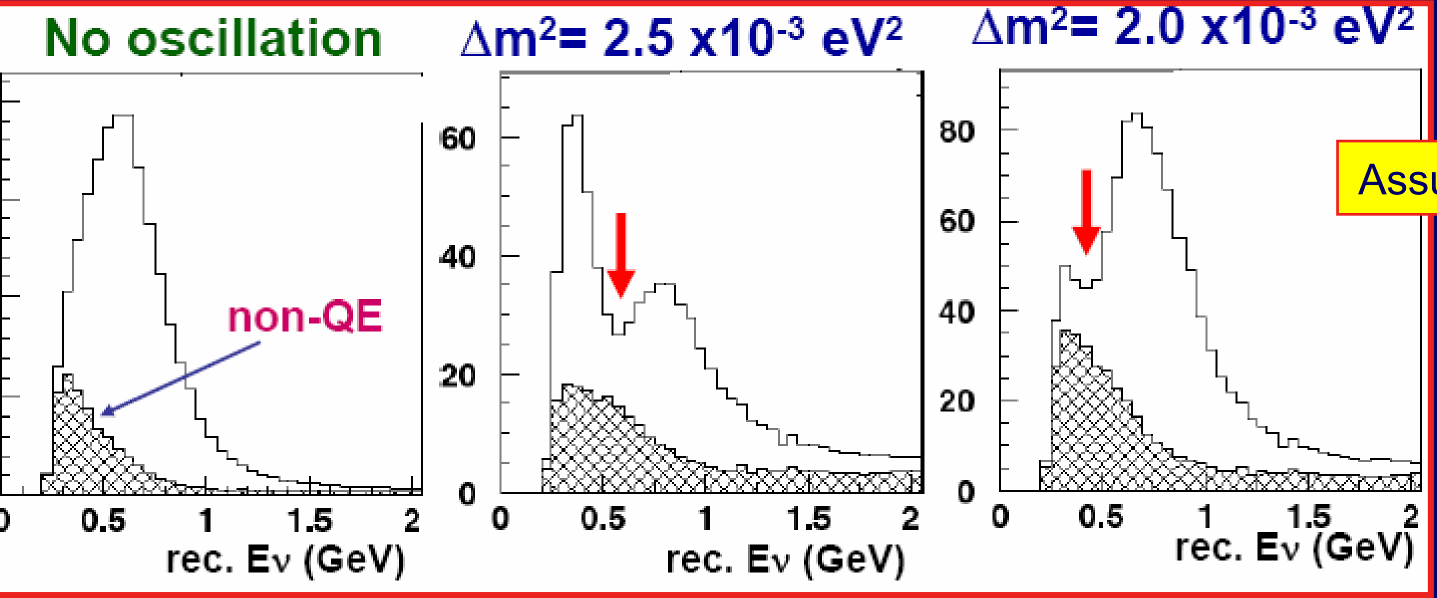


Importance of near detectors: difference in near/far spectra **main systematic error in K2K**

Expected systematics in T2K:

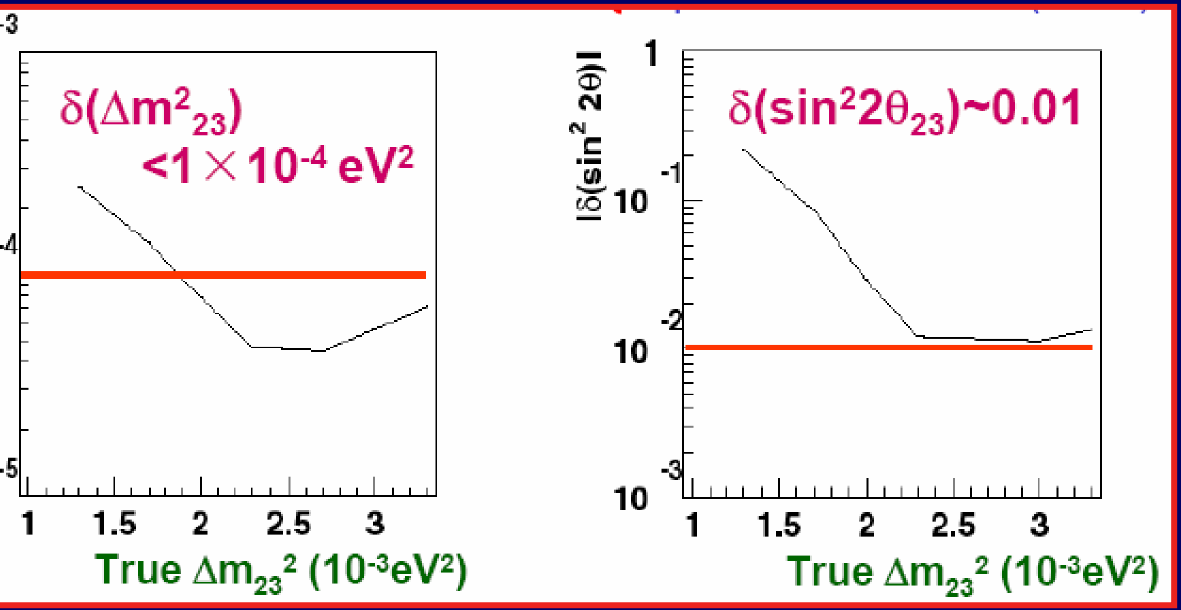
normalization	(5%)
non-qe/qe ratio	(5%)
E scale	(1%)
Spectrum shape	(20%)
Spectrum width	(5%)

T2K ν_μ disappearance



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

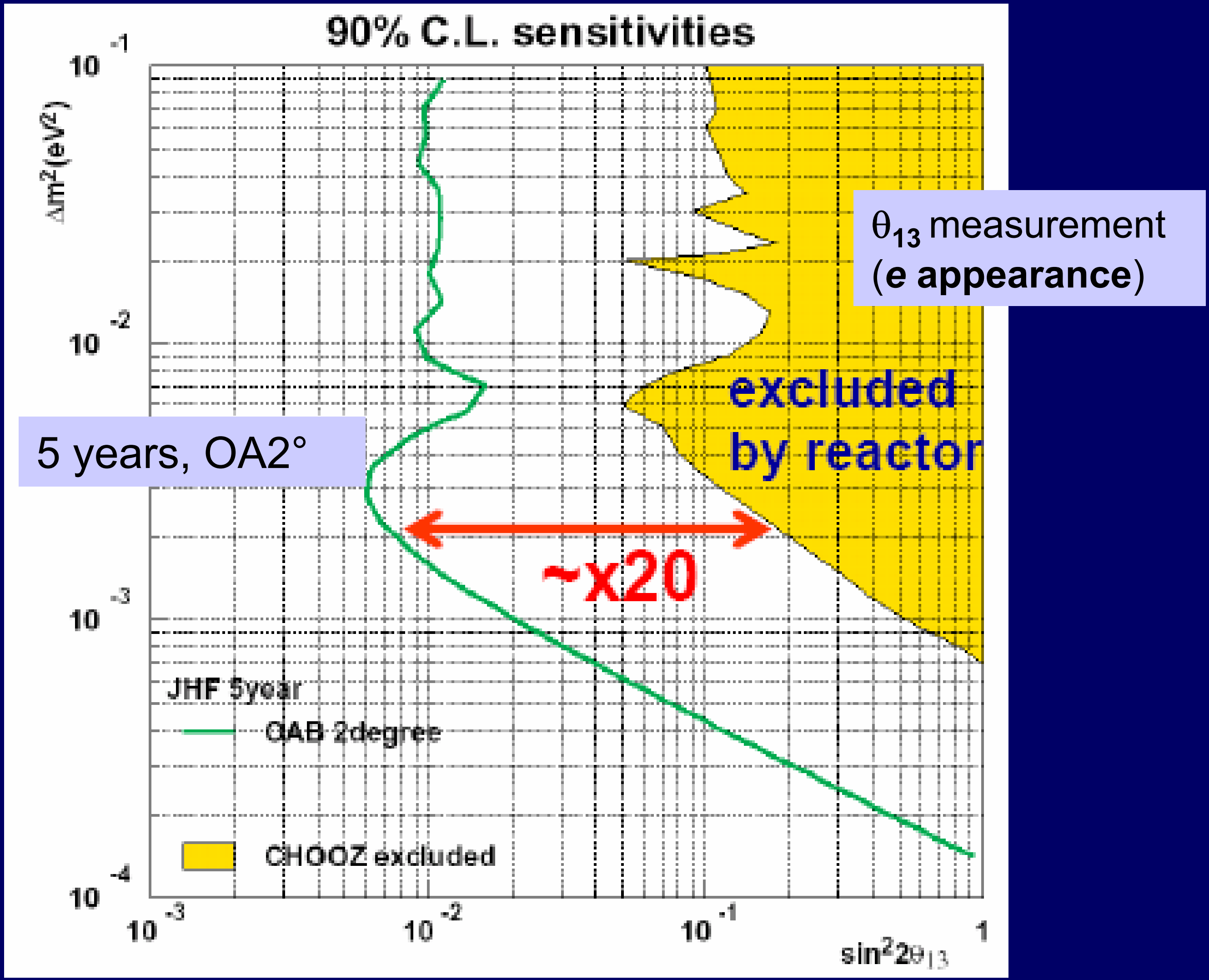
5 years running



Harvest for T2K (~2013-20

- 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 **0.01** (90% CL limit at **0.006**)

T2K ν_e appearance: measurement of θ_{13}



Sensitivity:

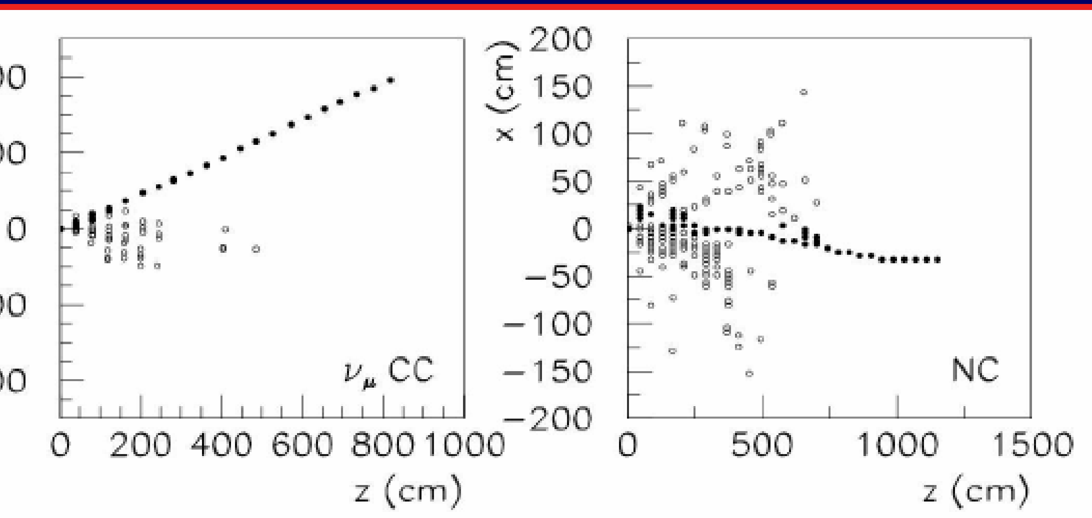
$\sin^2 2\theta_{13} > 0.006$ (90%)
$\sin^2 2\theta_{13} > 0.018$ (3σ)

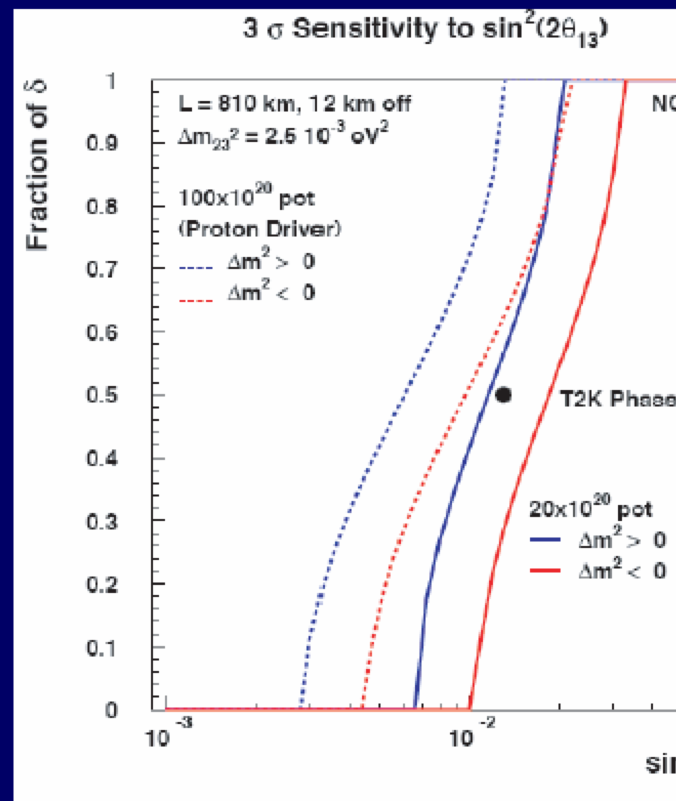
An off-axis experiment in the NuMI beam: NoνA

Start 2009-2010

- ecent proposal (March 04); nominal NuMI beam: 0.4 MW + upgrade?
- approved: 15 % of far detector by 2008. Completed by end 2011
- ar detector: 50 kton @ Ash River (MN) 810 km from Fermilab (12 km, mrad off-axis)
- echnique: particleboard/liquid scintillator with fiber/APD R/O (or RPCs)
- ear detector: same as far, 1 ton fid. mass; also use MINERVA ?

unlike T2K, NoνA is sensitive to matter effe





- nventional detector design: well known technique of low nsity, fine grained calorimeters (*e.g.* CHARM II at CERN)
- **st of about $150 M**
- te: this is basically a single task detector (schedule, npetition with T2K, etc.)

Comparison between MINOS, T2K and NoνA

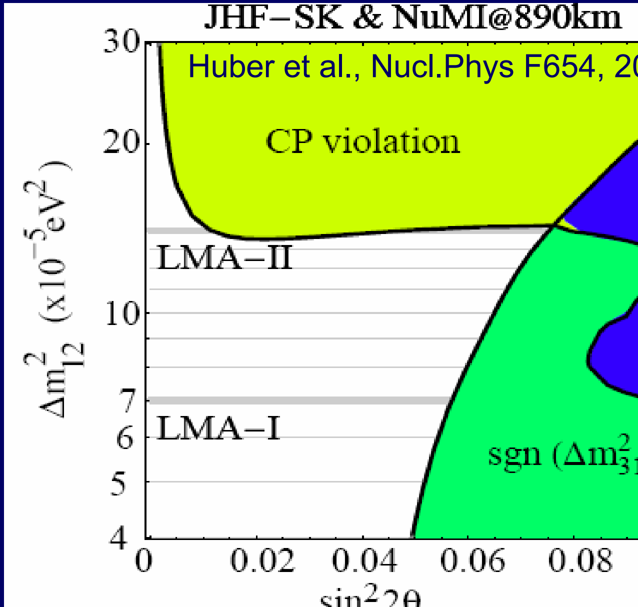
Assume 5 years running, Δm^2_{23}= 2.5 x 10^{-3} eV^2, 3σ evidence for non zero $\sin^2\theta_{13}$:

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)	2010-2014 ?	20 x 10^{20} 100 x 10^{20}	> 0.015-0.020 > 0.005-0.007

e Japanese project has an **existing** far detector and an **roved** beam (in construction): **possibility of discovery**

addition, it would be worth considering elsewhere new eration detectors with an extended physics program

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



Pin down CP phase and mass hierarchy

Detecting CP violating effects

est method:
n 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 !

<u>larger effects for long L: 2nd oscillation maximum</u>

wever…

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

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

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

<u>impact on the detector design</u>

…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:

$E \approx 5$ GeV → $L \approx 3000$ km

<u>flux too low with a conventional LBL beam</u>

Mass hierarchy from matter oscillation

trinos oscillating through matter (MSW effect):

ferent behavior of different flavors due to the presence of electrons in the medium

ditional phase contribution to that caused by the non zero mass states.

ymmetry between neutrinos and antineutrinos even without CP violating phase in the matrix

e related oscillation length L_M, unlike L_V (vacuum), is independent of the energy

an example L_M (rock) is ~ 10000 km while L_M (Sun) ~ 200 km

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

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

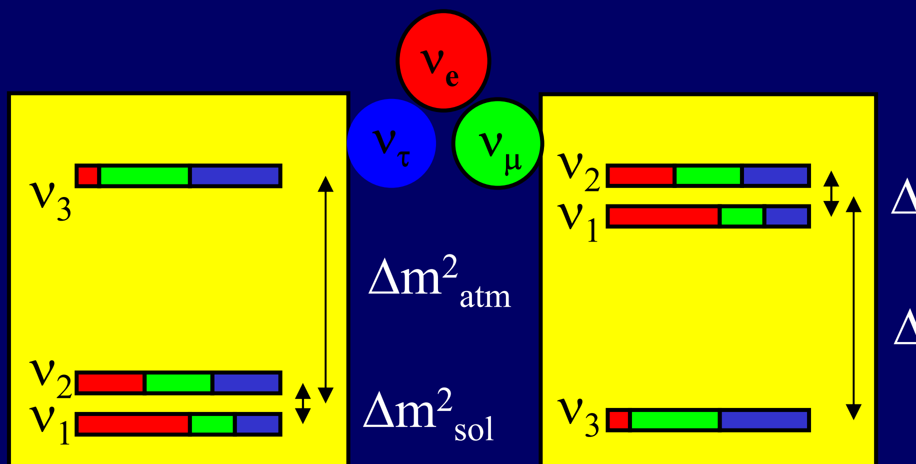
with

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

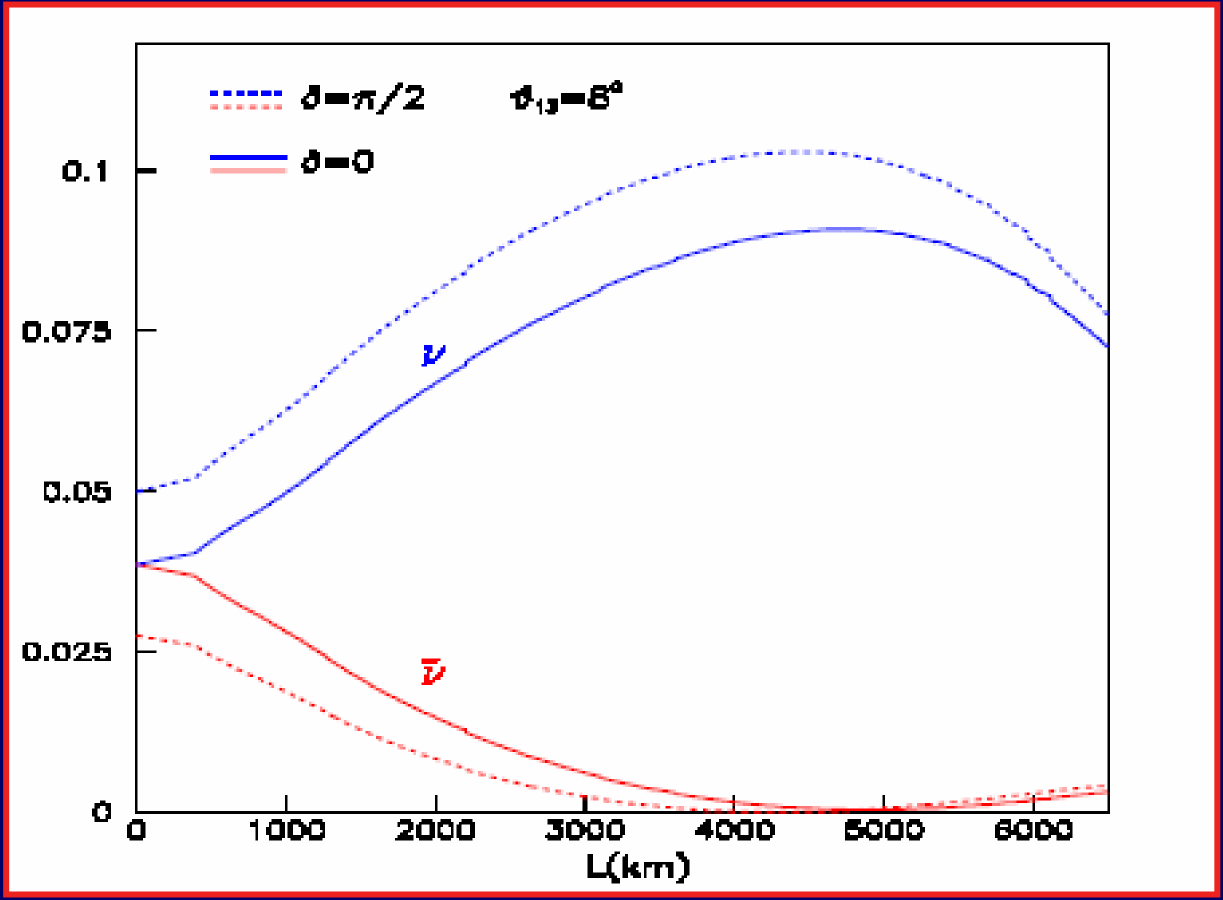
he measurement of this asymmetry one can determine whether Δm^2_{23} is positive or negati rarchy)

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

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



For $E_\nu \sim E_R$ large amplification of $P(\nu_\mu \rightarrow \nu_e)$ at long distances



Experiments with 2nd generation Super-Beams, Beta-Beams, ν-fact

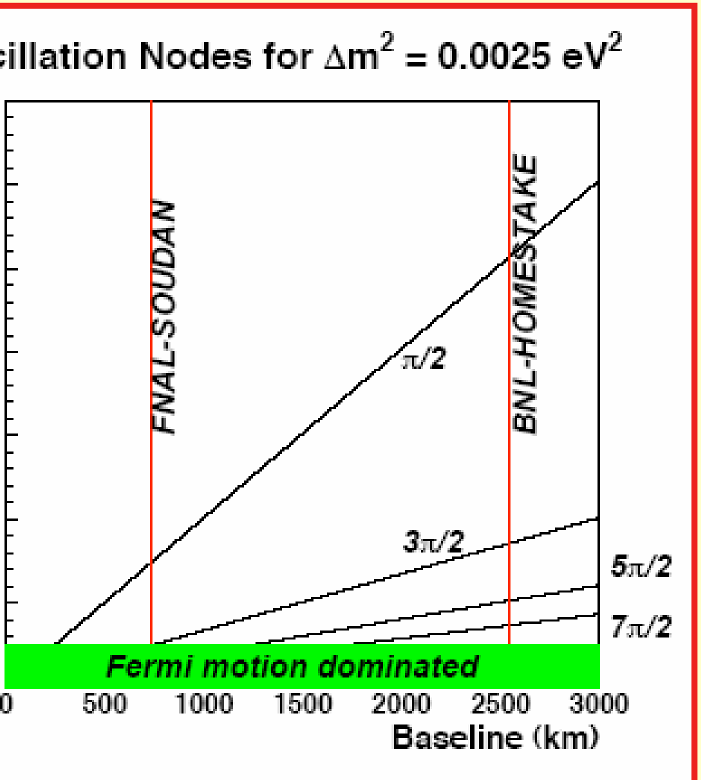
Start 2015-

Golden goal: detect CP violation (if θ_{13} not zero!)

gh intensity is mandatory: two possible approaches for **L/E** :

ong/high (*e.g.* BNL-Fermilab projects):
- matter effects increase signal (E_{max2}/E_{max1}
- CP effects increase with L (3π/2 vs π/2)

hort/low (*e.g.* CERN-SPL to Frejus):
- below threshold for BG (? …Fermi motion)
- atmospheric neutrino BG
- antineutrino x-section small
- Fermi motion limits resolution for μ events
- For both approaches: need to know ν_e BG energy dependence

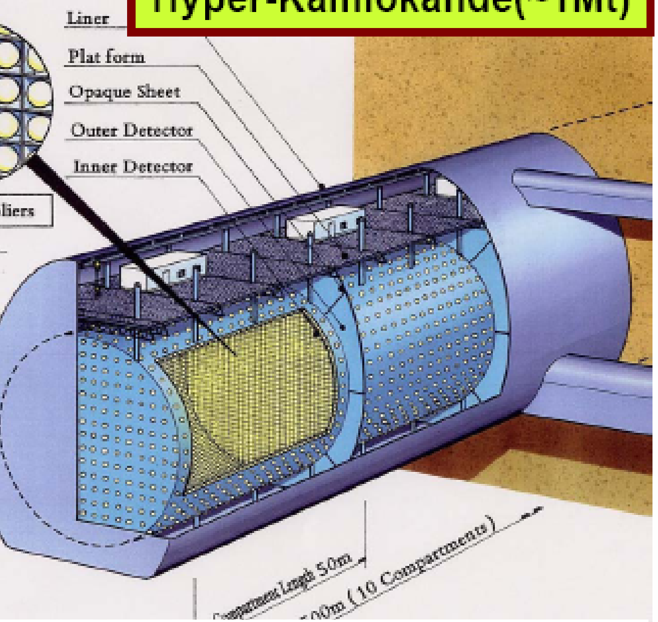


General remarks:

- a beam/detector complex of this type, given its complexity and c must be considered as a facility running for a few decades and h able to accomplish general purpose neutrino and astroparticle physics experiments as well as ultimate matter stability searches

- There can be degeneracies in the determination of matter and C effects: more (complementary) experiments are needed to solve

2nd Phase (201x~?)
Hyper-Kamiokande(~1Mt)



t: 48m x 50m x 250m each

DETECTORS

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

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

However, this is not the only possibility

Water Cerenkov technique

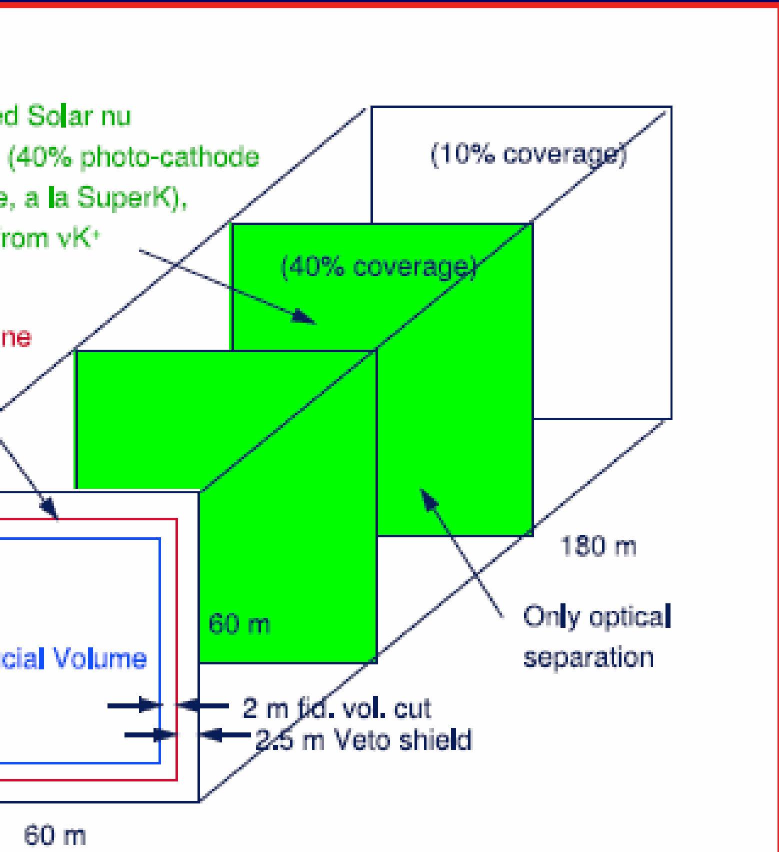
- efficient for ‘few’ or 1-ring events (QE), small x-section, large detector m
- good π^0 rejection if γ are well separated
- at low energy confusion between μ and π tracks
- can go down with energy threshold (5 MeV for 40% coverage) ?
- well established in Japan: success of SK but limited experience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

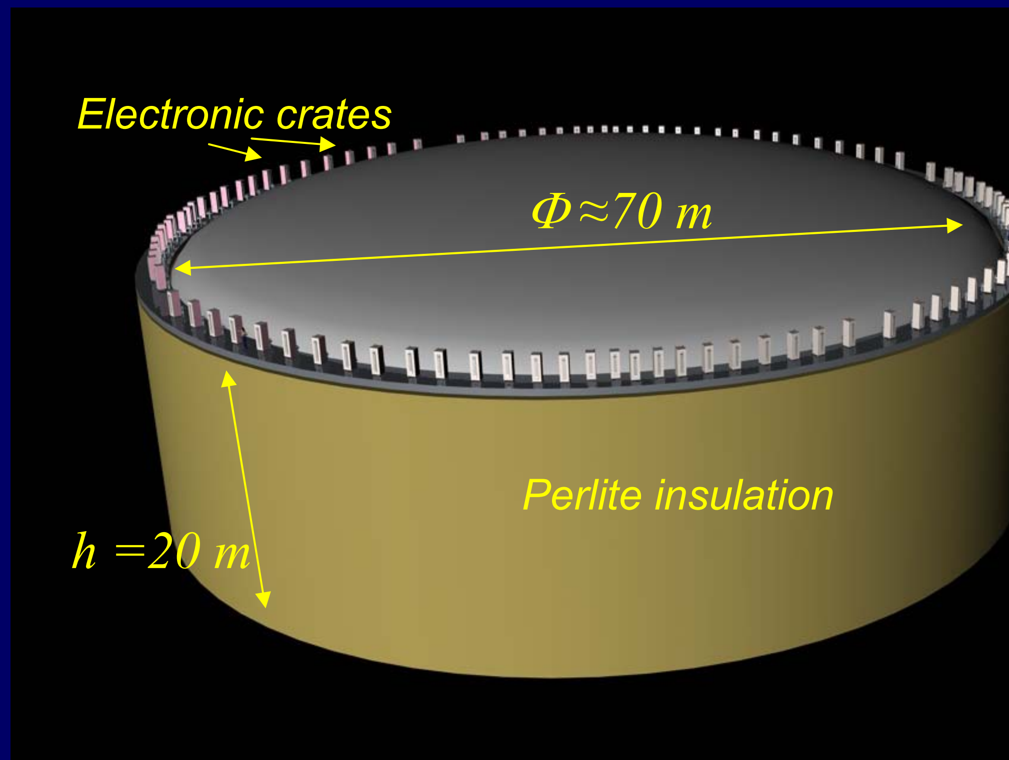
A fine grained detector can be alternative/complementary: liquid Argon TPC

00-600 kton Water Cerenkov
↔
100 kton LAr TPC

higher efficiency (multi prong interactions) and BG reje

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

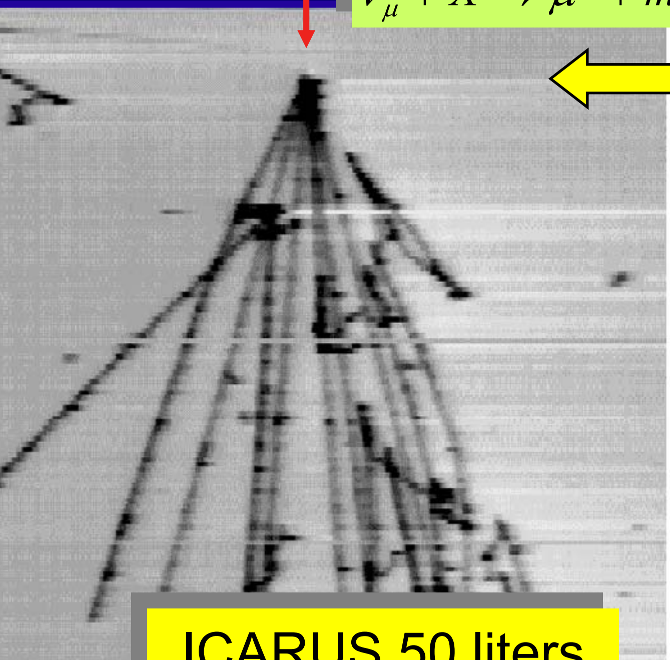




0 kton UNO-like Water Cerenkov

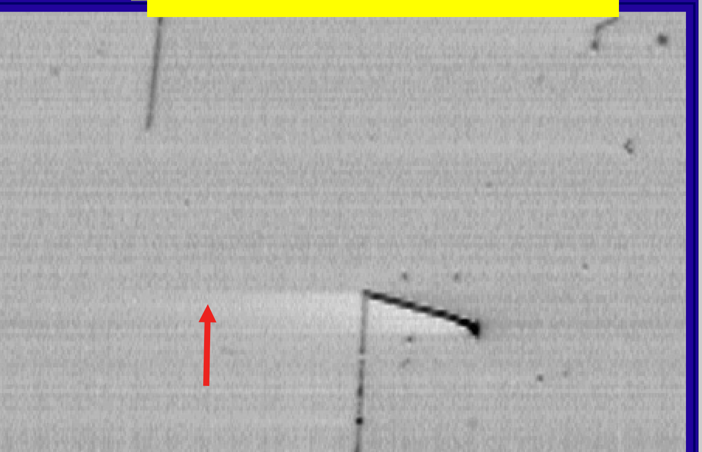
Neutrino detection: LAr TPC vs water Cerenkov

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



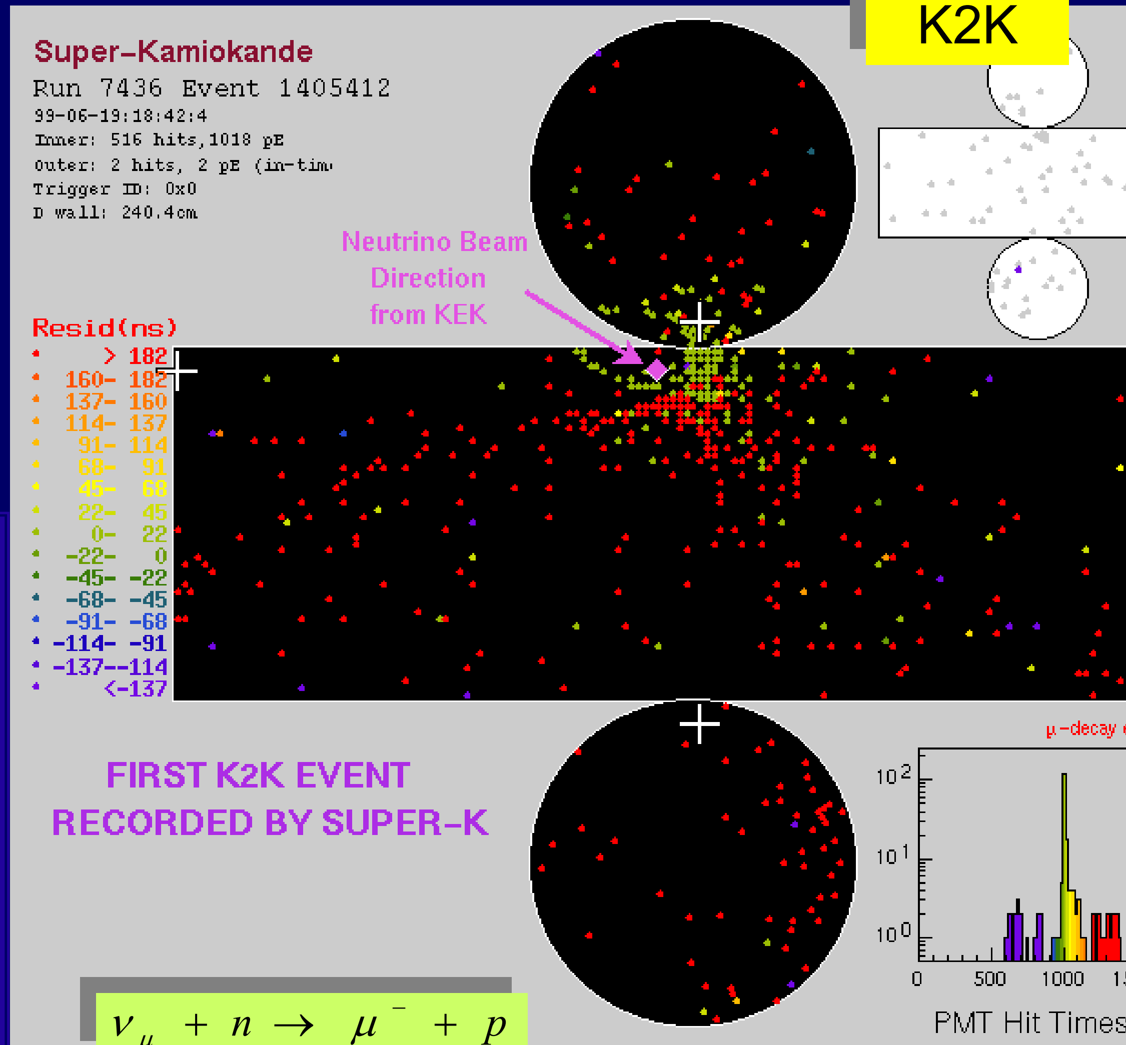
Multi prong event detection not possible with water Cerenkov

ICARUS 50 liters



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

K2K



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

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

The ICARUS experience plays a role, but the dete is very challenging:

R&D plan must be identi and executed

full scale prototype ?

Japanese program phase 2: short L, low E

ensity up to 4 MW

ector mass up to 1 Mton

matter effects: assume
s hierarchy determined
where

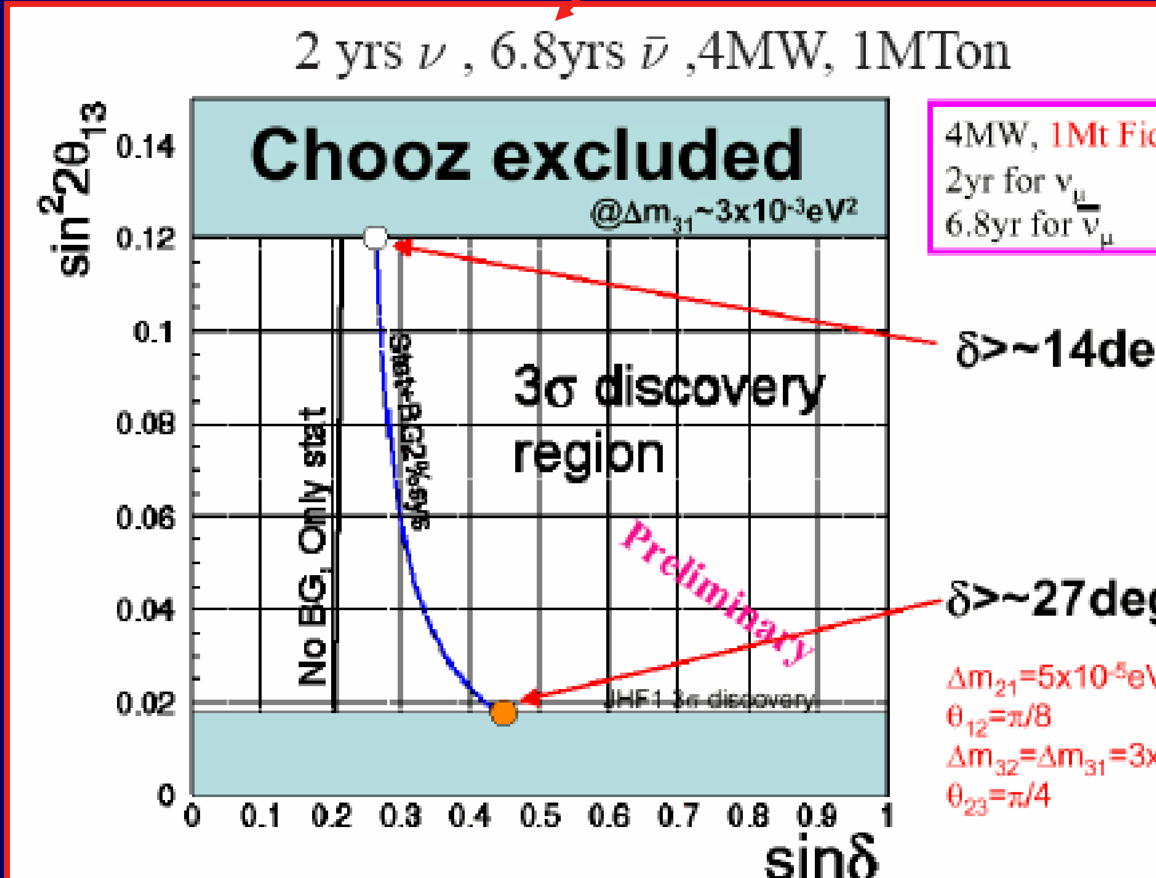
Major T2K beam upgrade, new Hyper-K detecto

1) low energy: low $\pi°$ BG

2) gigantic water Cerenkov: good

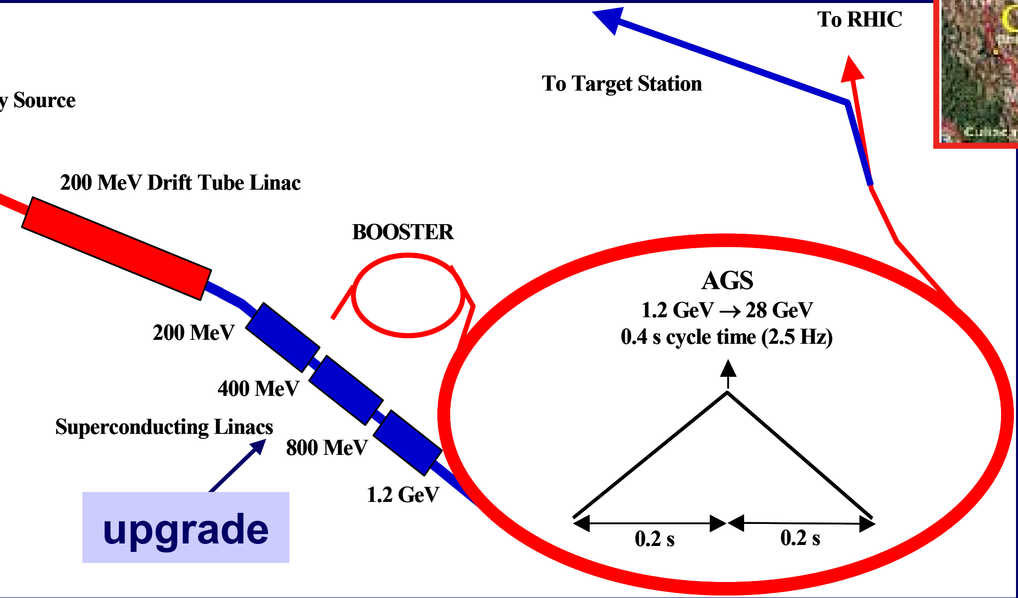
demanding requirements: 2% syst. from BG subtraction and 2%
data selection

low $E\bar{\nu}$→ low x-section



program: BNL proposal

- BB sent to large distance (> 2000 km)
- pgrade the 28 GeV AGS up to 1 MW
- eed a new 1.2 GeV LINAC
- o target R&D (while needed for 4 MW)
- NO Cerenkov detector in a NTL' Lab (?)



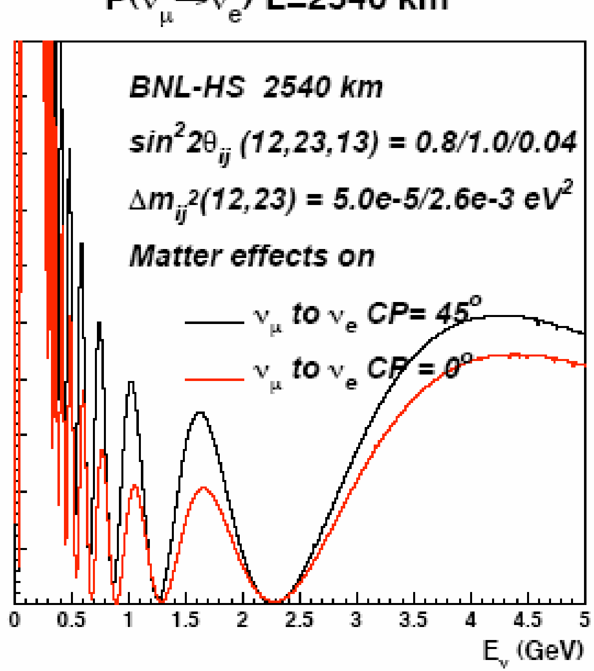
STRATEGY

The wide energy spread requires high signal/BG ratio:

G: only 1-ring events to reject most of π_0 (2-rings)

gnal: at high E matter effects increase statistics, at low E the long L makes neutrinos at the 2nd o
cillation maximum, hence increasing CP violating effects by 3-5 times

oal: detect CP violation with **only neutrino** (no antineutrino) exposure (2 maxima)

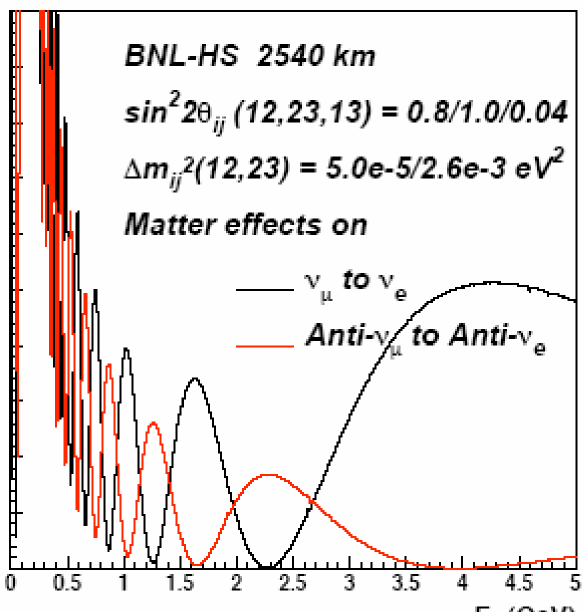


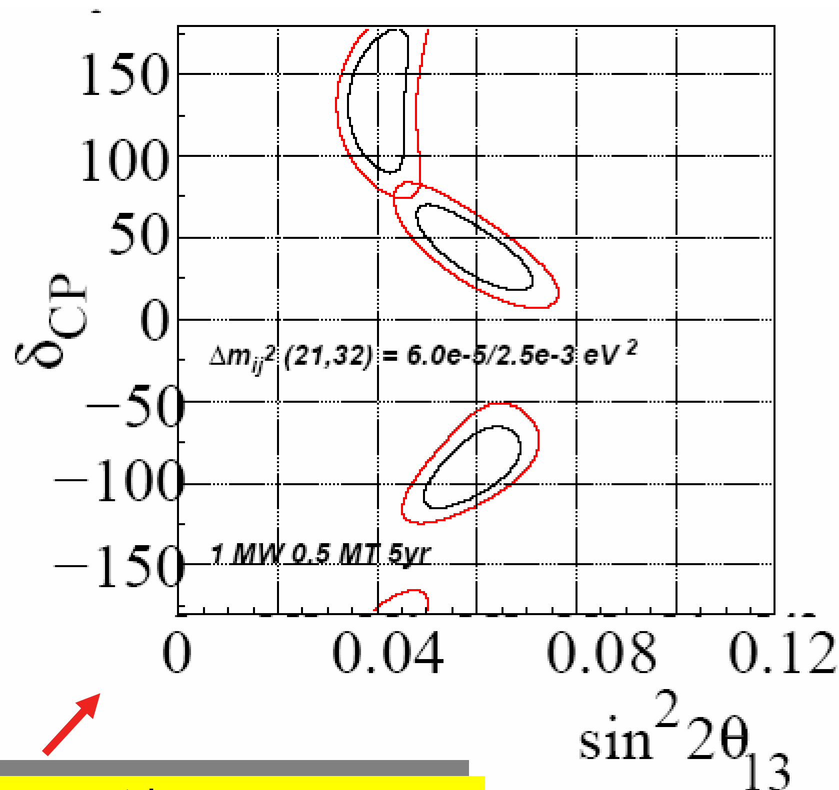
E = 0.5-1 GeV : Δm^2_{12} region

1-3 GeV : large CP effects

> 3 GeV : Δm^2_{23} region: matter enhanced (suppressed) ν_μ ($\bar{\nu}_\mu$)

P($\nu_\mu \rightarrow \nu_e$) CP= 45 deg





- 5 years neutrino exposure
- 500 kton detector mass
- assume normal hierarchy

Oscillation parameter determination with ν_e appearance

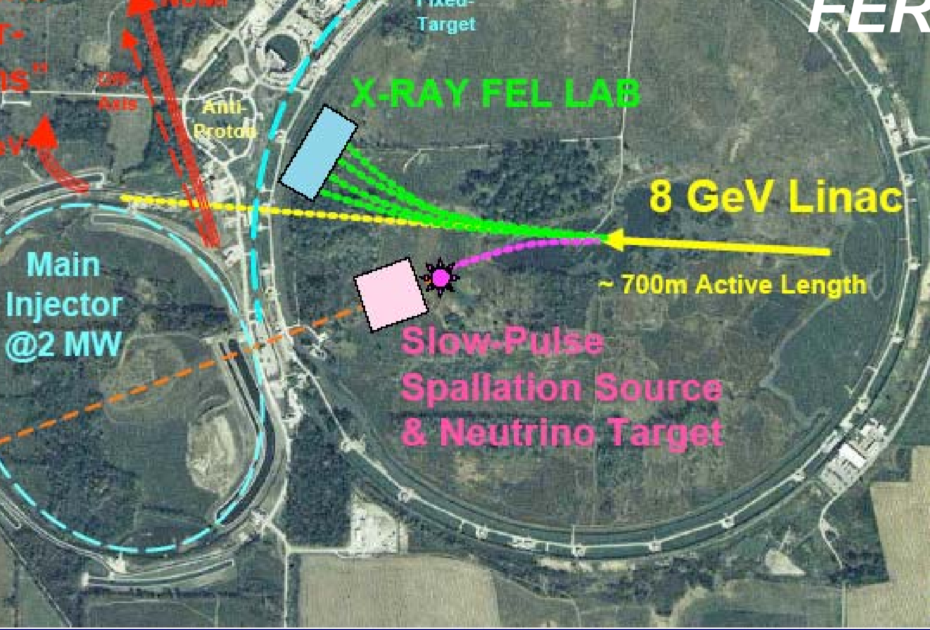
Assume $L > 2000km$, wide band beam

Δm^2_{32}, Δm^2_{21}, θ_{12} well known.

3 neutrino generations. $\Uparrow$ = large change $\uparrow$ = small change

		$\sin^2 2\theta_{13} > 0$	$\Delta m^2_{32}(> 0, < 0)$	$\delta_{CP} = (\pi/4, -\pi/4)$	$\theta_{23}(< \pi/4, > \pi/4)$
ν	0 – 1.2 GeV	$\uparrow$	–, –	$\uparrow, \downarrow$	$\Uparrow, \Downarrow$
	1.2 – 2.2 GeV	$\uparrow$	–, –	$\Uparrow, \Downarrow$	$\downarrow, \uparrow$
	> 2.2 GeV	$\uparrow$	$\Uparrow, \Downarrow$	$\uparrow, \downarrow$	$\downarrow, \uparrow$
$\bar{\nu}$	0 – 1.2 GeV	$\uparrow$	–, –	$\downarrow, \uparrow$	$\Uparrow, \Downarrow$
	1.2 – 2.2 GeV	$\uparrow$	–, –	$\Downarrow, \Uparrow$	$\downarrow, \uparrow$
	> 2.2 GeV	$\uparrow$	$\Downarrow, \Uparrow$	$\downarrow, \uparrow$	$\downarrow, \uparrow$

FERMILAB project: 8 GeV SC LIN



- upgrade Main Injector from 0.3 to 2 MW
- shoot ν's to Homestake (1290 km)
- usual question about the far detector: 500 kton water C or 100 kton LAr TPC ?

Another issue: NuMI off-axis phase-II ?

Suppose T2K+others → $P(\nu_\mu - \nu_e) = 0.02$

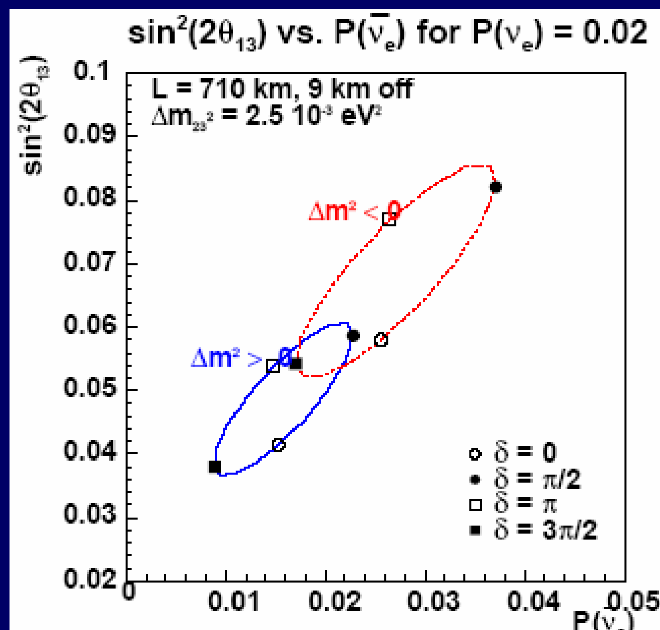
1st max: CP ~ matter

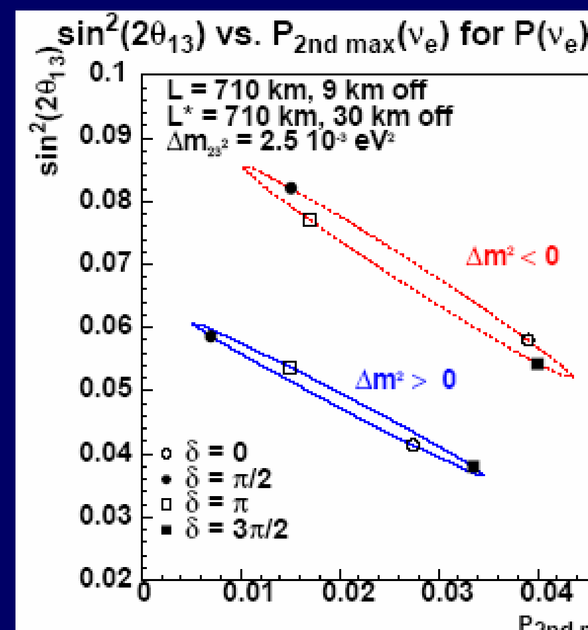
2nd max: matter E_{2nd} / E_{1st} and CP= 3 x (

ible luxurious scheme (?)

1300 km) large underground tor for ν and astroparticle cs

xis: fine grained 20-50 kton tor (LAr TPC ?) at shallow with improved BG rejection

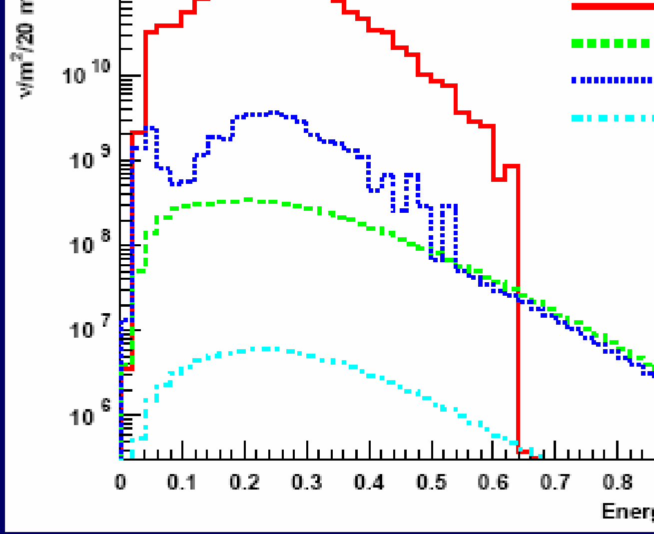




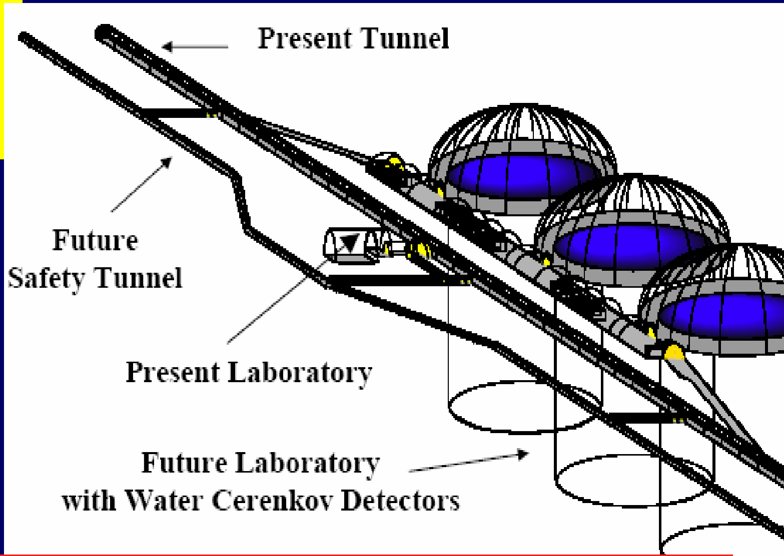
European program(s)

isioned neutrino facility
RN SPL (2 MW): low E, 10^{23} protons/year
er option: Beta-Beam (CERN original R&D)
y role of CERN: logistic and scientific center regardless
ar detector site/technology

ear-far' envisioned site: Frejus laboratory
derground laboratory 140 km from CERN
operation agreement: IN2P3/CNRS/DSM/CEA & INFN
ernational laboratory for underground physics
sy access but safety issues (highway tunnel)
verns have to be excavated (goal: 2008)
rease working group composition ?



Detector at Frejus: 500-1000 kton w
Cerenkov and/or 100 kton LAr TPC



For Cerenkov detector option:
commissioning with beam by 2015-2017

SPL option

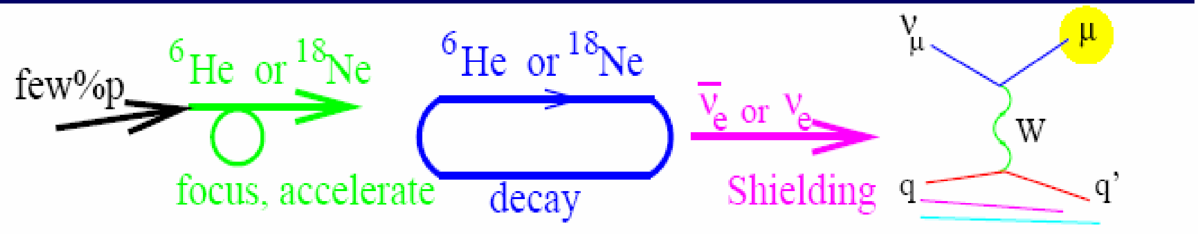
ption well retained at CERN (interesting for arge community)

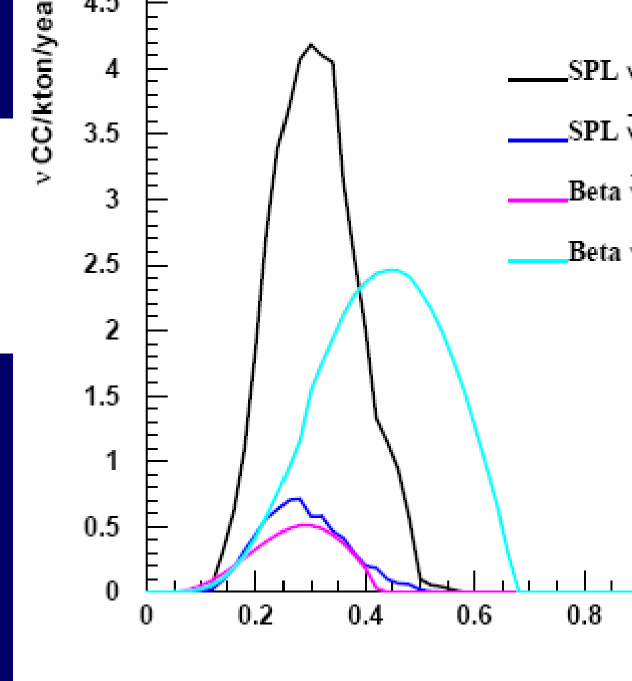
ow energy neutrino beam: < 500 MeV

small antineutrino rate, and small x-section: eed long antineutrino run (8 out of 10 years)

ν_e and $\pi°$ BG

eta-Beam option





inal idea born at CERN (P.Zucchelli)

oactive ions produced, boosted (γ ~ 100) and stored

m: focused, known energy, pure flavor composition

eam BG

om Ne^{18} ~ 2-10x10^{10}/s $\bar{\nu}_e$ from He^6 ~ 10-30x10^{10}/s

ions can be stored at the same time

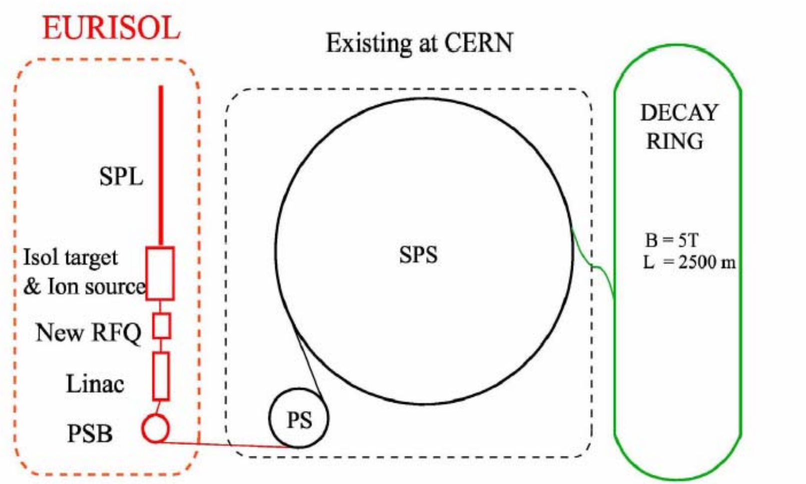
ronmental issues (radiation)

arch for $\nu_e \rightarrow \nu_\mu$ oscillations:

asier detector task (μ detection)

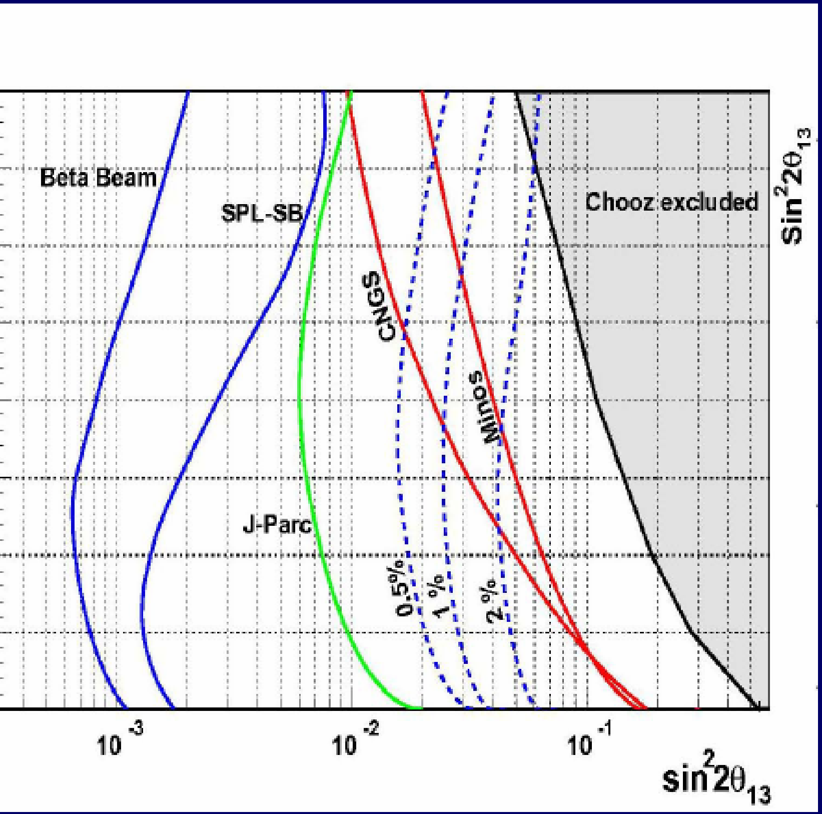
owever, need good event reconstruction:
ns in NC can fake muons

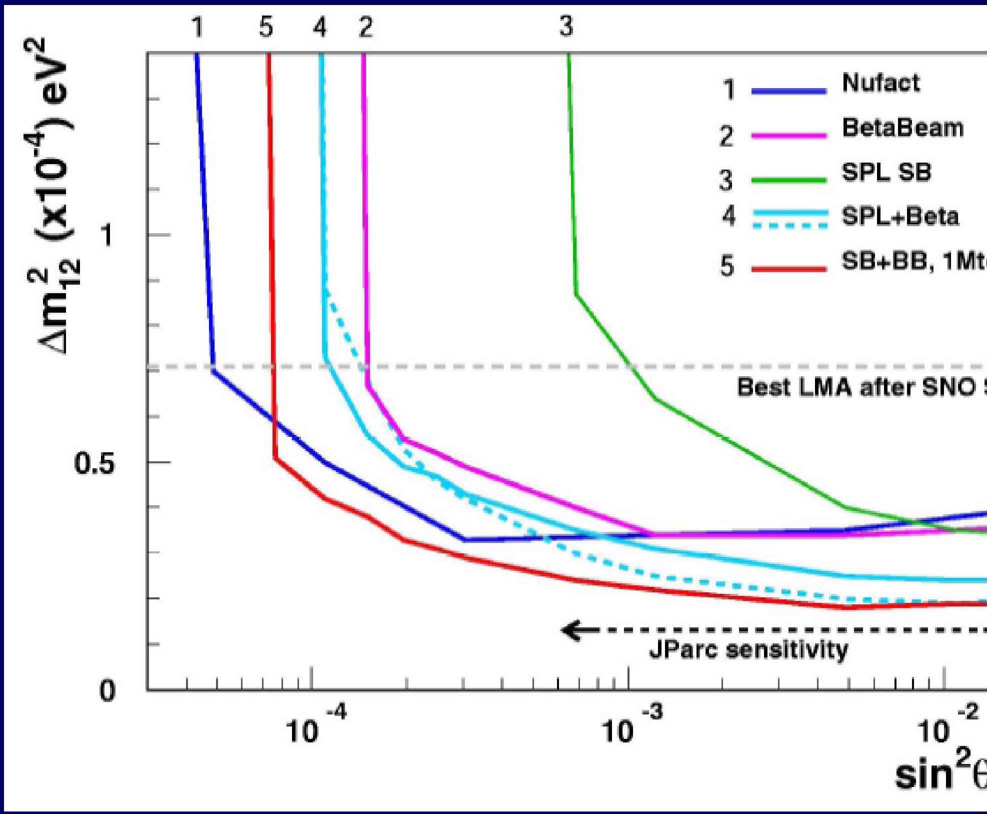
w energy makes pion production below
renkov threshold



Performance

Hope: realize the SPL and/or the Beta-Beam from 2009 to 2015 and then commission for physics





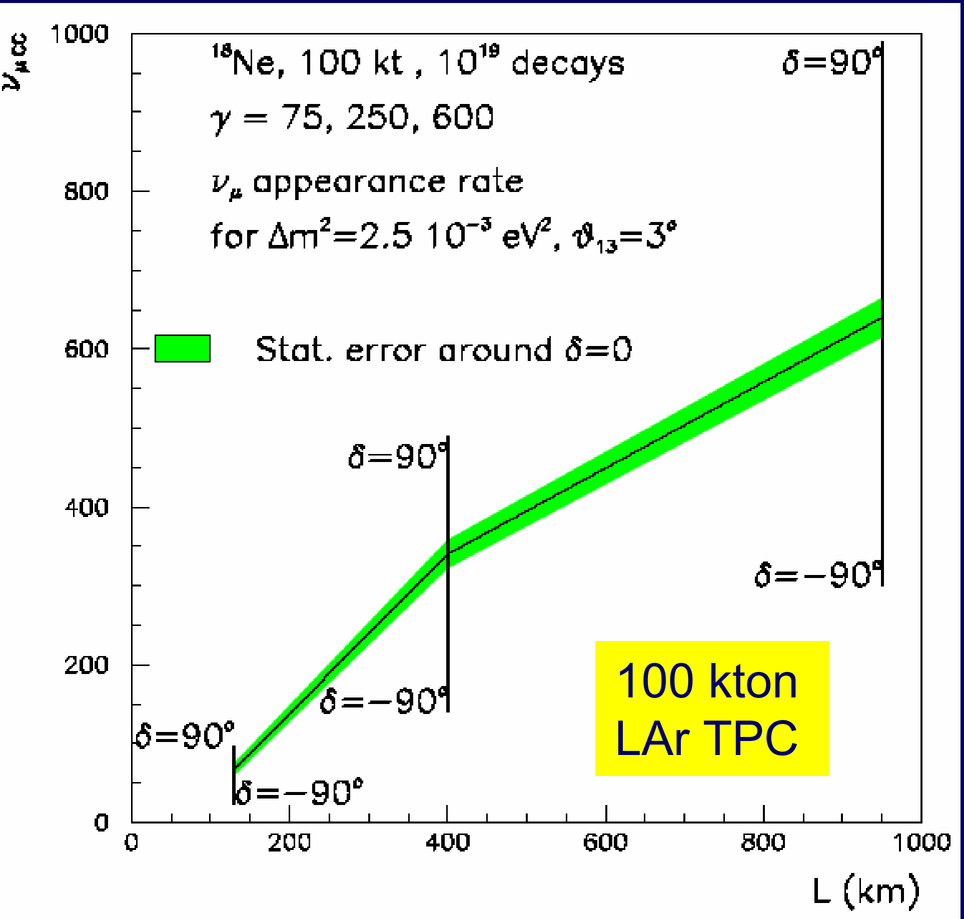
5 years run at δ=0 (90% CL)

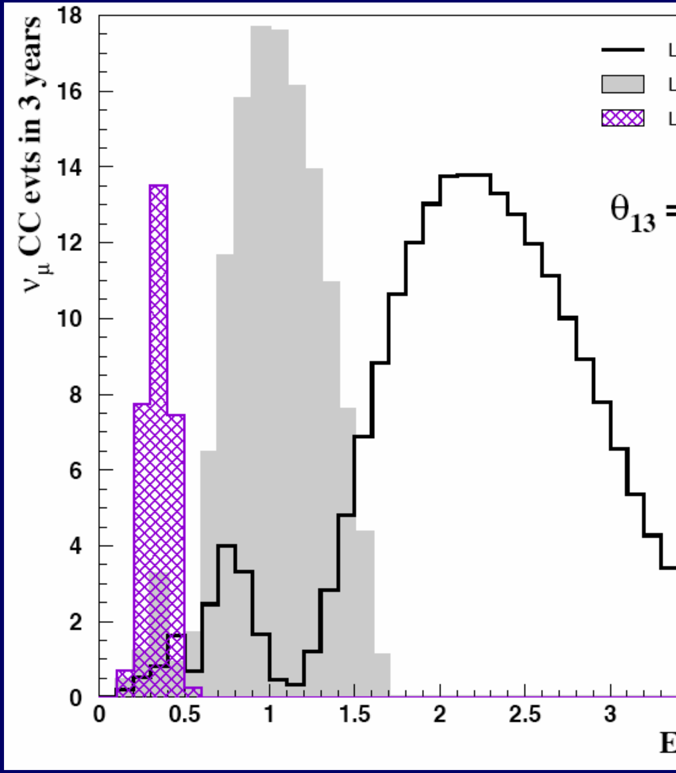
3σ sensitivity to maximal CP violation (10 years)

A high energy Beta-Beam? Improved performance

gh-energy (γ) Beta-Beam can be realistically made sing an upgraded super-conducting SPS (1 TeV)

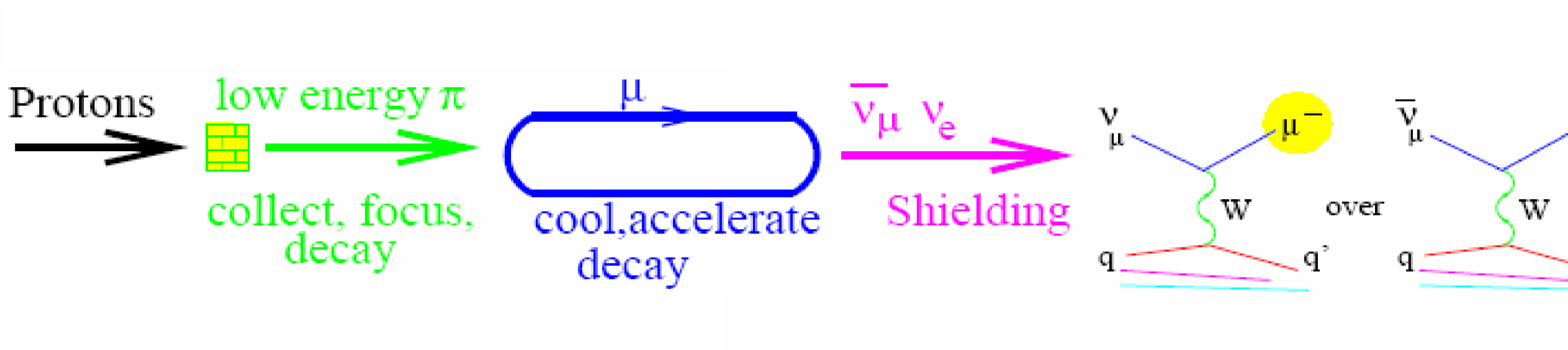
1.1 x 10^{18} ^{18}Ne and 2.9 x 10^{18}
baseline: L = 130, 400, 950 kr
γ = 75, 250, 600





If high energy would be chosen, possible far sites exist:
e.g. LNGS, Oulu (Finland), Cuprum salt mines (Poland), etc.

st but not least: Neutrino Factories
the ultimate neutrino beam experiments?



bviously, a great opportunity for neutrino physics!

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

(personal) concluding remarks

he glory of the massive neutrino! The evidence for neutrino oscillation mostly built-up with **sol** **tmospheric** and **reactor** neutrino experiments is today very robust. This has opened the way to recision studies of the mixing matrix with **accelerator** neutrino experiments, together with future rojects on direct mass measurements, double-beta decay, reactor, solar and atmospheric neutrin

he mass of neutrino is the first (and so far the only) indication of **physics beyond the SM**. If eutrinos are Majorana particles this gives clues to the questions of fermion masses, to the questi hy 3 families, to mass hierarchy. Lepton number violation could explain the baryon asymmetry rough leptogenesis. Massive neutrinos may contribute to the energy density of the Universe. **A ascinating study has just started and must be vigorously pursued in parallel to collider EW hysics.**

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

he detection of **matter** and of **CP violating effects** will likely require a further generation of xperiments using high intensity (> 1 MW) neutrino facilities with more massive detectors. At prese wo options are being considered: a 500-1000 kton **water Cerenkov** detectors (à la SK) and 50-10 ton **liquid Argon TPCs**. Solving degeneracies calls for different experiments with different arameters

(personal) concluding remarks (cont.)

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.

Concerning the **neutrino beams**, a factor ~10 boost in the intensity is required. **Super-Beams** a the natural approach, based on improved LINAC or Boosters. Synergies are expected with other fields and this can increase the probability of success (funding). As far Europe (CERN) is concerned, the possibility of building **Beta-Beams** (of low and/or high energy) must be explored, being peculiar and 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.

The issue of a **Neutrino Factory** (no more than one!) has to be considered with care. It constitutes the ultimate neutrino facility with unprecedented features but its construction would represent a huge investment for the entire community. This must be well motivated considering the state of the field at the moment of the decision to go and the synergy/competition with other possible schemes/approaches and with other large projects in particle physics (*e.g.* muon or electron collider). Its main task must be the precision study of **CP violation**, whereas the discovery could well be made with Super- o Beta-Beams, with an eye to the unexpected.

(personal) concluding remarks (cont.)

The neutrino community is **very active** and many ideas and proposals are on the floor both for th facilities and for the detectors. However, for the next (next-to-next) generation we will have to dea with 100-200 M€ (500-800 M€) experiments and with 300-500 M€ (1000-1500 M€) beam facilities

The **cost and the complexity** of these projects demand a **strong worldwide coordinated effor** between researchers and agencies, similarly to what occurs in other fields, *e.g.* for collider physic There will be resources available for a very small number of large facilities/detectors in the world. **Complementarity** of approaches and techniques is mandatory.

Therefore, 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). The **international competition** should not be neglected: one has always to p attention to it aiming at performing (in time) good quality measurements.