The ϑ_{13} angle of the leptonic mixing matrix: experimental status and perspectives

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LNF

1998−2002: a golden age for neutrino physics

"Evidence for oscillation of atmospheric neutrinos"
The **Super−Kamiokande** Collaboration, Phys. Rev. Lett. 81 (1998) 1562

"Direct Evidence for Neutrino Flavor Tranformation from Neutral−Current Interactions in the Sudbury Neutrino Observatory"
The **SNO** Collaboration Phys. Rev. Lett. 89 (2002) 011301

"First results from KAMLAND: evidence for reactor anti−neutrino disappearance"
The **KAMLAND** Collaboration. Dec 2002. hep−ex/0212021

"Indication of neutrino oscillations in a 250 KM long baseline experiment."
The **K2K** Collaboration. Dec 2002. hep−ex/0212007

No more wandering in the dark...

Test the flavours involved in the oscillation and the oscillation predictions (appearance of new flavours and/or sinusoidal pattern of disapperance)

MiniBoone $\Rightarrow$ confirm/disprove LSND (sterile neutrinos?)

ICARUS+OPERA $\Rightarrow$ first direct evidence of appearance of new flavours

MINOS $\Rightarrow$ sinusoidal pattern + flavour partecipation (NC/CC)

} Improved precision on atm. Oscillation parameters

The final question:

Can we perform precision CKM physics also in the leptonic sector? (determination of real angles and phases, ~~CP~~, test of unitarity etc.)

The ϑ_{13} angle

Neutrino oscillations possible for massive neutrinos with a non trivial mismatch between mass (ν_i) and gauge eigenstates (ν_α)

$$\boxed{\nu_\alpha = \sum_i U^*_{\alpha i} \nu_i} \qquad Amp[\nu_\alpha \to \nu_\beta] = \sum_i U^*_{\alpha i} e^{-i m_i^2 \frac{L}{2E}} U_{\beta i}$$

Three light active neutrinos (ν_e , ν_μ , ν_τ) $\Rightarrow$ U is a 3x3 (approximately) unitary matrix and can be parameterised with three angles and 1 (+2) phases. Recover the CKM formalism ($s_{ij}=\sin\vartheta_{ij}$) :

$$U = R(\vartheta_{23}) \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{bmatrix} R(\vartheta_{12})$$

Nature simplified a lot the formulas...

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sum_{jk} U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k} e^{-i \Delta m^2_{jk} L/2E}$$

Only differences of (squared) masses enter the formula (no info on absolute mass scale).

Three neutrinos $\Rightarrow$ two differences Δm^2_{12} and Δm^2_{23}

Nature has chosen for us a strong hierarcy:

$$\Delta m^2_{12} \ll \Delta m^2_{23} \approx \Delta m^2_{13}$$

"solar scale" "atmospheric scale"

If L/E is tuned to maximise the P at Δm^2_{23} ("atmospheric scale") all the terms proportional to $\sin^2 (\Delta m^2_{12} L/E)$ are strongly suppressed

If the atmospheric scale dominates:

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\vartheta_{13} \sin^2 \Delta_{23}$$

$$P(\nu_e \to \nu_\mu) = \sin^2 2\vartheta_{13} \sin^2 \vartheta_{23} \sin^2 \Delta_{23}$$

$$P(\nu_e \to \nu_\tau) = \sin^2 2\vartheta_{13} \cos^2 \vartheta_{23} \sin^2 \Delta_{23}$$

$$P(\nu_\mu \to \nu_\mu) = 1 - 4\cos^2 \vartheta_{13} \sin^2 \vartheta_{23} (1 - \cos^2 \vartheta_{13} \sin^2 \vartheta_{23}) \sin^2 \Delta_{23}$$

$$P(\nu_\mu \to \nu_\tau) = \cos^4 \vartheta_{13} \sin^2 2\vartheta_{23} \sin^2 \Delta_{23}$$

$$\Delta_{23} \equiv 1.27 \Delta m^2_{23} L / E$$

Note that:

- ✔ No CP violating phase appears
- ✔ If $\vartheta_{13}=0$ "atmospheric" $\Rightarrow$ pure $\nu_\mu \to \nu_\tau$

  "solar" $\Rightarrow$ pure $\nu_e \to \nu_\mu$

ϑ_{13} measure the degree of decoupling of "atmospheric oscillation" from "solar oscillations"

Subdominant contributions:

In fact:

- ✓ if Δm^2_{12} is not too small (e.g. $5\ 10^{-5}\ eV^2$) $\rightarrow$ **OK!! Kamland!!**
- ✓ if $\sin^2 2\vartheta_{13}$ not too small (e.g. $O(10^{-2} - 10^{-3})$)

we can feature subdominant effects in terrestrial experiments (Superbeams or Neutrino Factories) to

- ✓ **measure the CP violation phase**
- ✓ **measure precisely $\sin^2 2\vartheta_{13}$**
- ✓ **measure the sign of Δm^2_{32}**

} CKM like precision physics!

the size of $\sin^2 2\vartheta_{13}$ is the missing link to assess the potentialities of the third generation neutrino oscillation experiments

What we know experimentally on $\sin^2 2\vartheta_{13}$?

The "golden channel" is ν_e disappearance

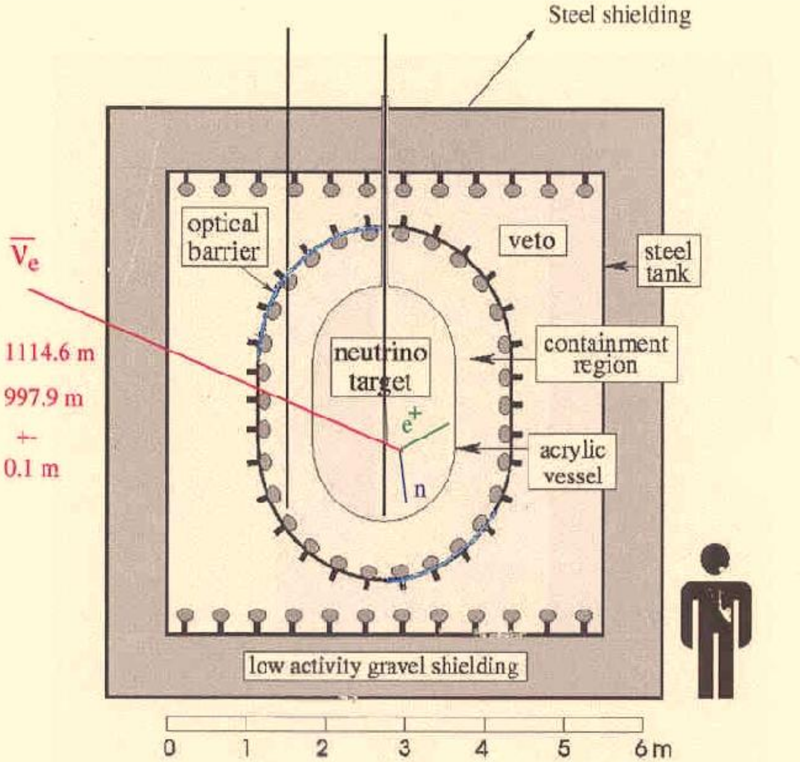
LO approx. $$P(\nu_e \to \nu_e) = 1 - \sin^2 2\vartheta_{13} \sin^2 \Delta_{23}$$

NLO $$P(\nu_e \to \nu_e) = 1 - \sin^2 2\vartheta_{13} \sin^2 \Delta_{23} - \frac{1}{2} \cos^2 \vartheta_{12} \sin^2 2\vartheta_{13} \sin^2 2\Delta_{31} \sin^2 2\Delta_{21} + (\cos^4 \vartheta_{13} \sin^2 2\vartheta_{12} + \cos^2 \vartheta_{12} \sin^2 2\vartheta_{13} \cos 2\Delta_{31}) \sin^2 \Delta_{21}$$

Reactor experiments with L ≈1 Km and E ≈ a few MeV

In fact they test $\bar{\nu}_e \to \bar{\nu}_e$ i.e. the CPT coniugate of $\nu_e \to \nu_e$

CHOOZ



Target : 5.57 m^3 of Gd loaded scintillator (0.09 %)

Region II and III : 127.9 m^3 of high-flash scintillator

192 PMT's on the geode (130 pe/MeV)

48 PMT's for the veto

Detection technique:

$$\bar{\nu}_e\, p \rightarrow e^+\, n$$

+H = 2.2MeV

+Gd = 8MeV

2γ (2x511keV)

Prompt pulse (e^+): 1.2−8 MeV

Delayed pulse within 2−100 μs

(n+Gd): 6−12 MeV

Background from reactor−OFF

Fit of the event rate versus termal power of the reactors

Sistematics

Reaction cross section	1.9%
Number of protons	0.8%
Detection efficiency	1.5%
Reactor power	0.7%
Energy absorbed per fission	0.6%
Combined	2.7%

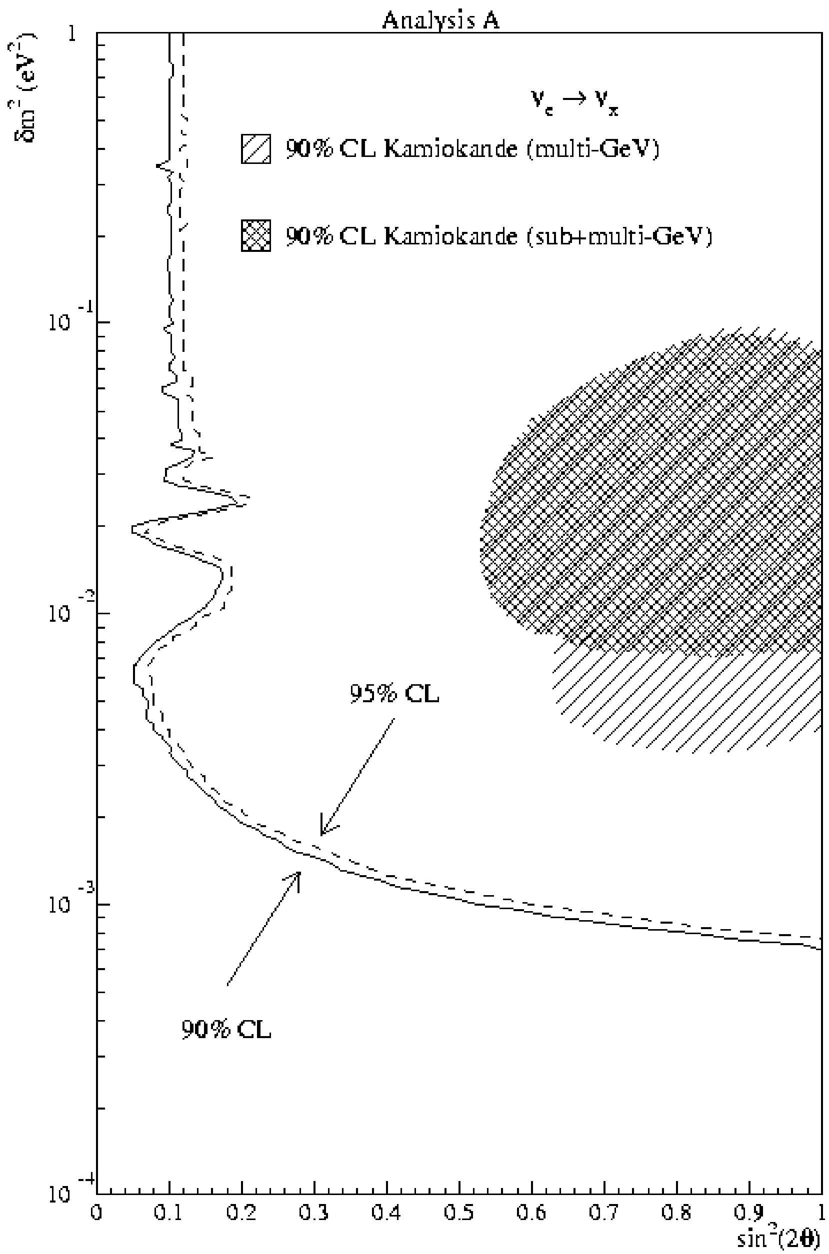
Results

Information coming from:

1) Overall rate
2) Positron E spectrum
3) Rate versus thermal power

No deficit has been observed

Results



$\sin^2 2\vartheta_{13} < 0.14$ (90%CL)

@ $\Delta m^2_{32} = 2.5\ 10^{-3}\ eV^2$

(LO approximation)

NLO results depend on solar parameters Δm^2_{12}, ϑ_{12}

- ✔ $\Delta m^2_{12} < 2\ 10^{-4}\ eV^2$ unchanged
- ✔ $\Delta m^2_{12} = 4\ 10^{-4}\ eV^2$, $\sin 2\ \vartheta_{12} = 0.5$

  $\sin^2 2\vartheta_{13} < 0.11$ (90%CL)

  (more stringent)

S.Bilenky et al. Phys.Lett.B538(2002)77

What we know from theory on $\sin^2 2\vartheta_{13}$?

Practically nothing!

Not surprising since:

- Origin of Yukawa sector of the SM completely unknown
- Leptonic mixing matrix seems VERY different from CKM (bilarge mixing among particle with big mass differences).
- Most of GUT inspired models need fine tuning to reproduce large mixings

Huge literature with predictions ranging from Chooz limits (10^{-2}) to 10^{-5} or even smaller...

A note of caution!

The discovery of $\sin^2 2\vartheta_{13} \neq 0$ has a scientific relevance by itself:
the full three flavour mixing of neutrinos is still unestablished

However it has an even higher strategical value:

The terrestrial experiments seeking for CP violation (JHF+HyperK, Neutrino Factories, etc) and making precision physics with the leptonic mixing matrix are extremely expensive. No funding agency will spend 2billion$ if in the meanwhile we don't have evidence of $\sin^2 2\vartheta_{13} \neq 0$: it could be the most impressive flop of the history of High Energy Physics!

How much can we improve the CHOOZ limit in the forecoming years?

Can we use the next generation Long Baseline experiments (MINOS+ICARUS+OPERA)?

Tuned for $\nu_\mu \rightarrow \nu_\tau$ appearance. Could work also in $\nu_\mu \rightarrow \nu_e$ mode.

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4\cos^2\vartheta_{13}\sin^2\vartheta_{23}(1-\cos^2\vartheta_{13}\sin^2\vartheta_{23})\sin^2\Delta_{23}$$

$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4\vartheta_{13}\sin^2 2\vartheta_{23}\sin^2\Delta_{23}$$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\vartheta_{13}\sin^2\vartheta_{23}\sin^2\Delta_{23}$$

Precise measurement of ϑ_{23} (mainly MINOS)

Evidence of ν_τ appearance (mainly CNGS)

Search for sub−dominant mode $\nu_\mu \rightarrow \nu_e$ (ϑ_{23})

MINOS

ν_μ **source: (NuMI)**

120 GeV protons from FNAL Main Injector

ν_μ **from pion decay**

ν_e **contamination from K and muon decay**

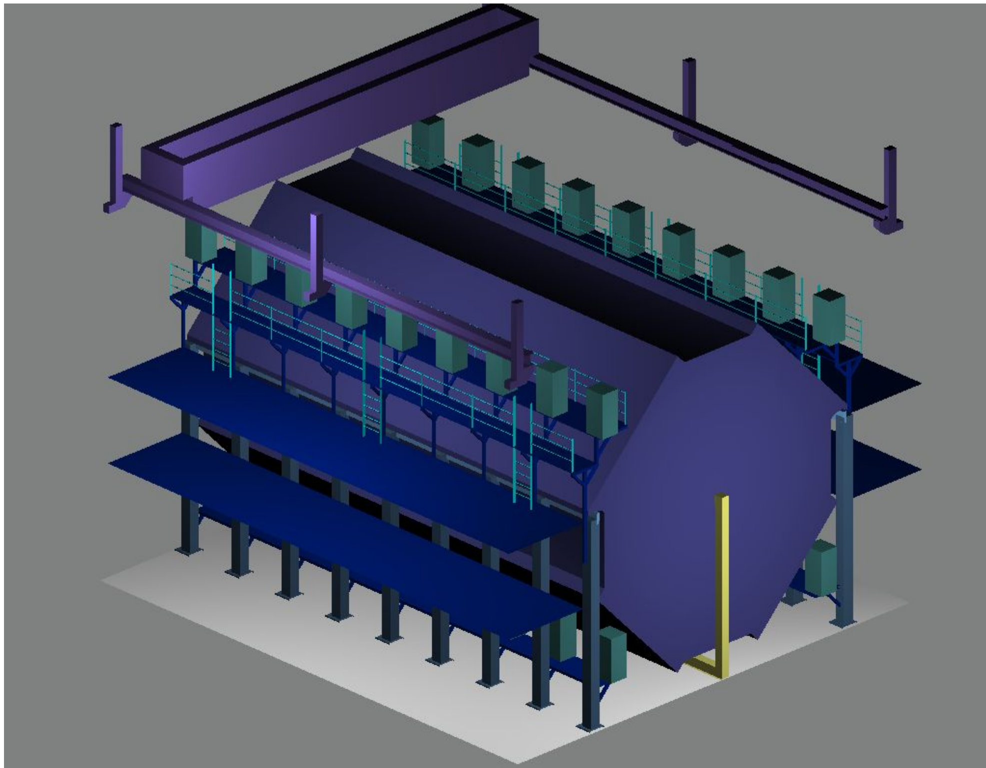
detectors: (MINOS)

1) 'Far' detector:

5.4 kT magnetized iron/scintillator tracker/calorimeter in Soudan mine

2) 'Near' detector:

980 T version of far detector at FNAL

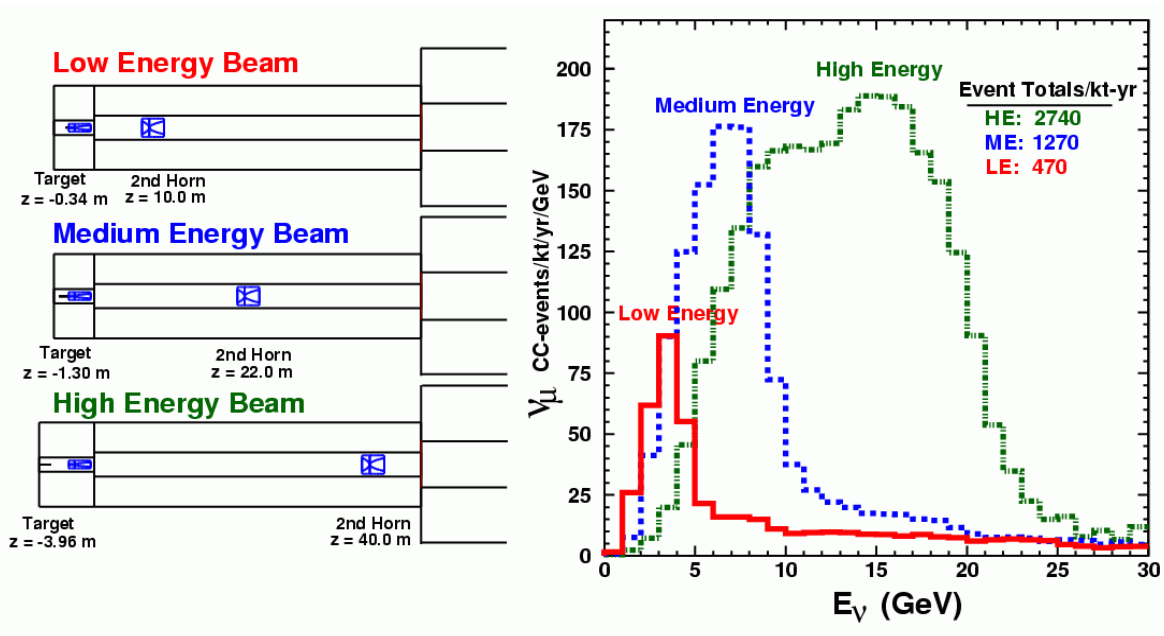


MINOS is a **coarse** grain calorimeter

- 2.5 cm thick iron slabs
- Plastic scintillators with 4.1 cm granularity (thickness 1 cm)
- Toroidal magnetic field (<B>≈1.2 T)

However,

- The NuMI beam can be tuned at the oscillation maximum (about 2 GeV for L≈730 Km)
- A near detector helps to deal with systematics



Background

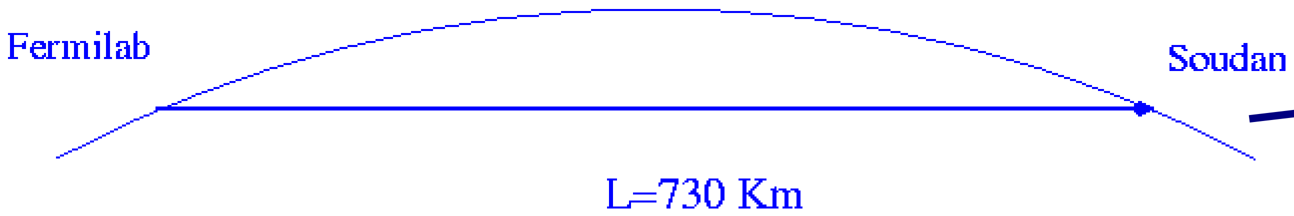
- NC events with π^0 production (high energy tail of ν_μ beam)
  low energy spectrum, e.m. shower development delayed
  (γ conversion), small visible energy (ν_μ outgoing)

- CC events with π^0 production and primary μ unidentified
  as before + visible primary muon

- ν_e contamination from the beam
  different energy spectrum, computed at near detector

- $\nu_\mu \rightarrow \nu_\tau$ oscillation with $\tau \rightarrow e\nu\nu$
  low visible energy (outgoing ν)

MINOS signal depends also on matter effect



ρ=2.8 g/cm^3

$$P(\nu_\mu \to \nu_e) = \sin^2 2\vartheta_{13}^m \sin^2 \vartheta_{23} \sin^2 \frac{\Delta m_{23}^2 L}{4E} S$$

$$S^2 \equiv \left(\frac{A_e}{\Delta m_{23}^2} - \cos 2\vartheta_{13} \right)^2 + \sin^2 2\vartheta_{13}$$

$$\sin^2 2\vartheta_{13}^m \equiv \frac{\sin^2 2\vartheta_{13}}{S^2}$$

Corrections of the order of $\pm 10-20\%$ depending on sign of Δm^2_{23}

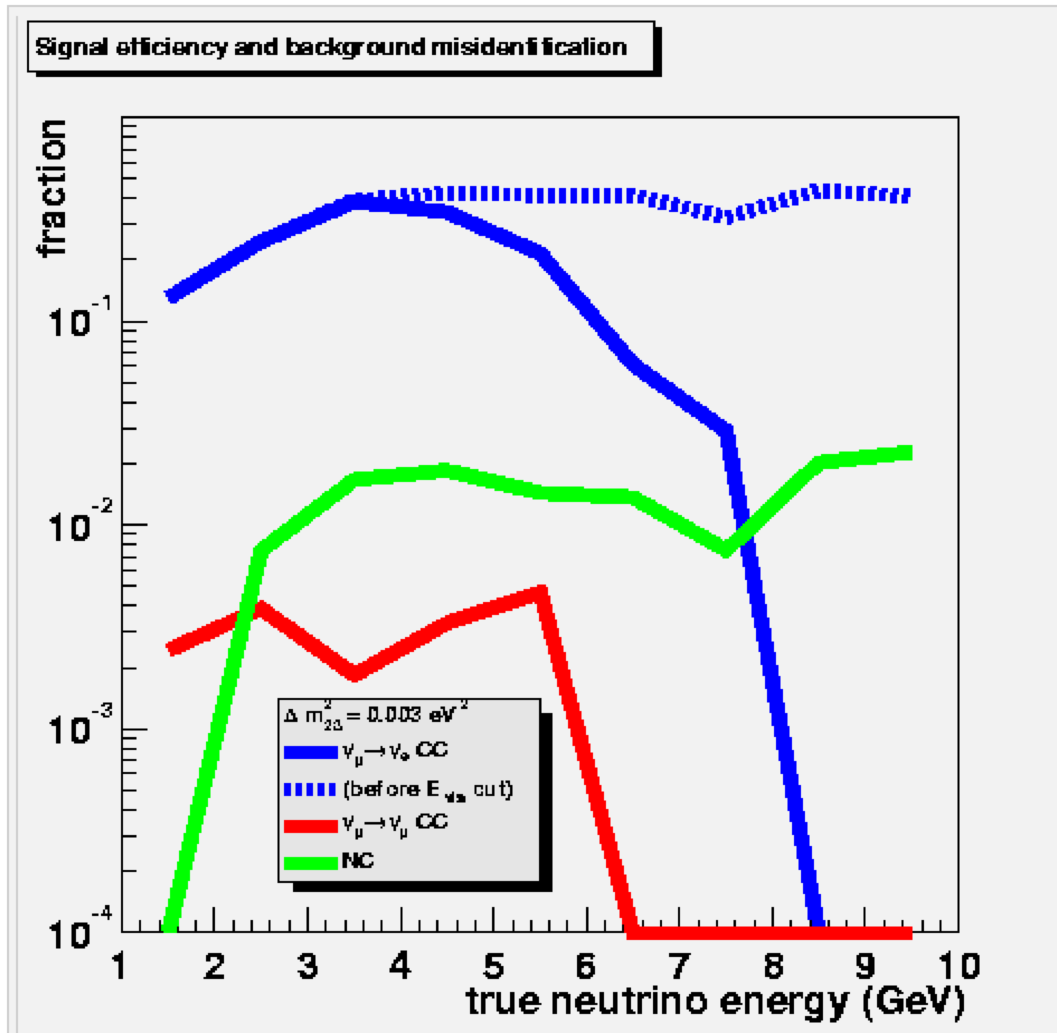
Event selection

Sequential cuts on:

- Fraction of E in highest cluster $E_{cluster} / E_{tot} > 0.7$
- N strips in highest cluster ≥ 9
- $P_{\mu} < 1$ GeV
- $100pe < E_{tot} < 600pe$

+

Neural net combining variables related to the event shape



Systematics

After event selection, background dominated by NC background

$\Delta m^2_{23} = 0.03\ eV^2$ $\sin^2 2\vartheta_{13} = 0.04$

signal	beam ν_e	ν_μ CC	$\nu_\mu \to \nu_\tau$	NC <10 GeV	NC>10 GeV
8.5	5.6	3.9	3.0	15.7	11.5

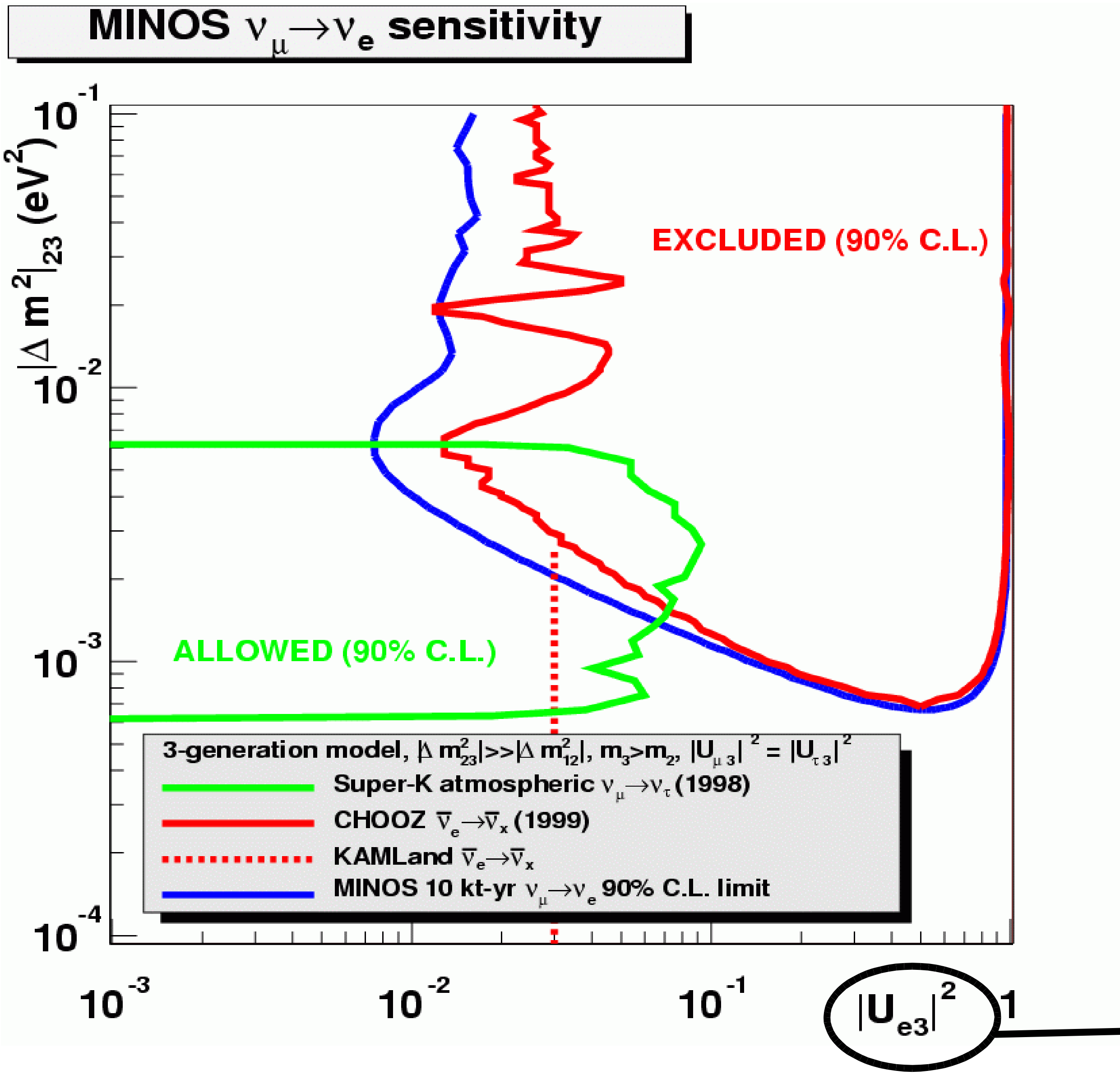
Near detector: NC rate with π^0 production
ν_e contamination

Still remaining uncertainty at the level of 10%

- ✔ Differences in near−far detector (geometry and overlapping events)
- ✔ Different angular coverage

Results will be limited by systematics after about 2 years of data taking

Results



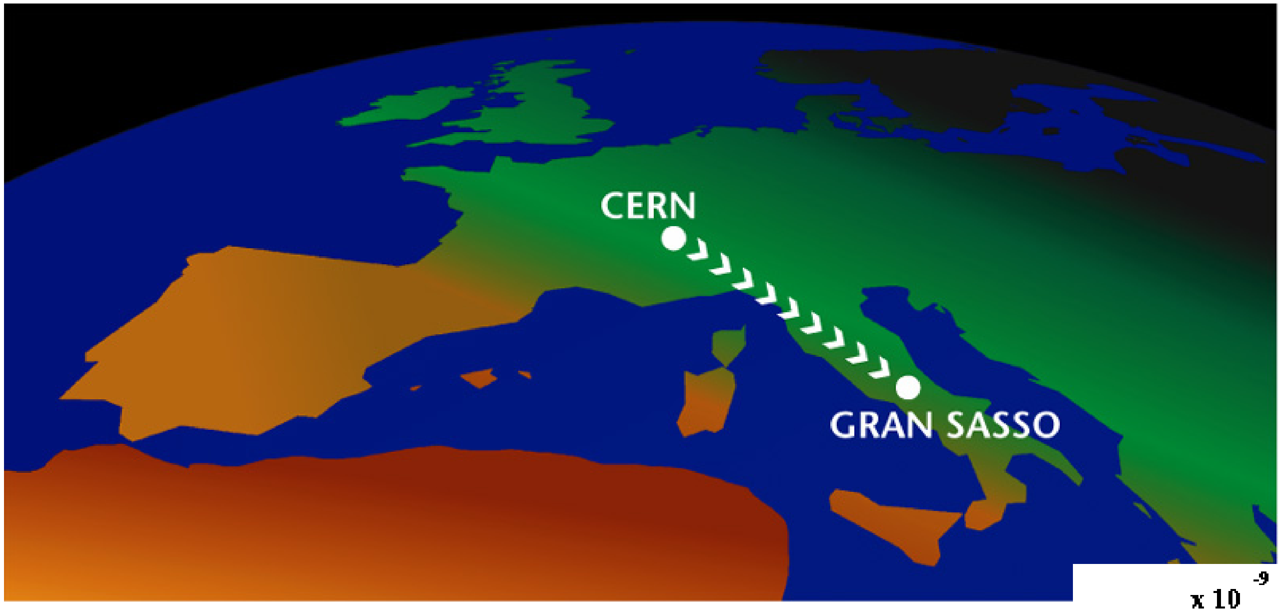
See M.Diwan et al. NuMI−Note−SIM0714

$= \sin^2 \vartheta_{13}$

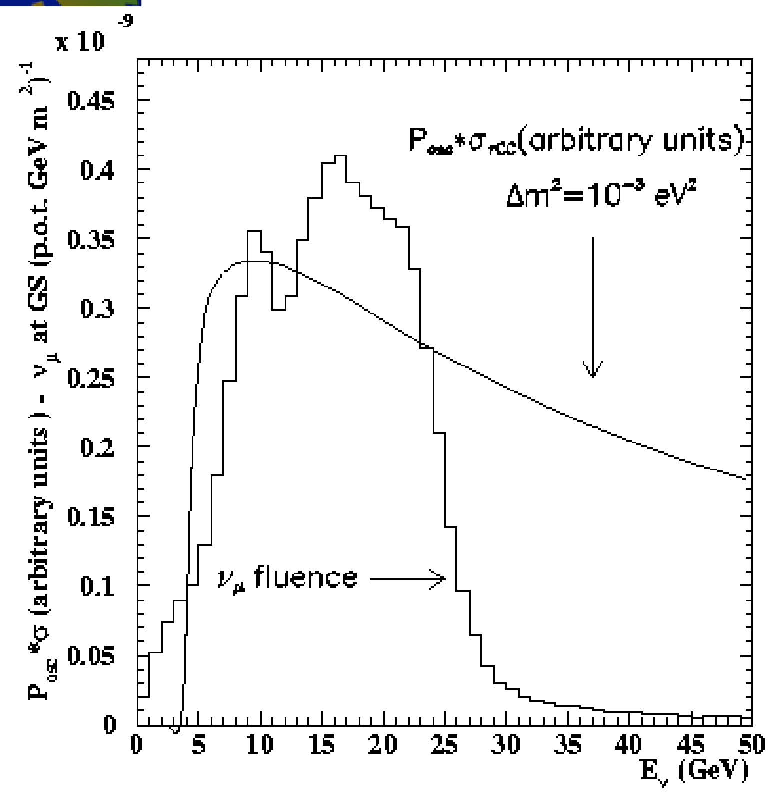
$\sin^2 2\vartheta_{13} < 0.06$ if $\Delta m^2_{23} = 0.025$ eV^2

(CHOOZ $\sin^2 2\vartheta_{13} < 0.14$)

Cern Neutrinos to Gran Sasso (CNGS)



An high energy neutrino beam for ν_τ appearance



E_ν is a compromise between tuning at oscillation maximum (low E) and high cross section for tau production (high E)

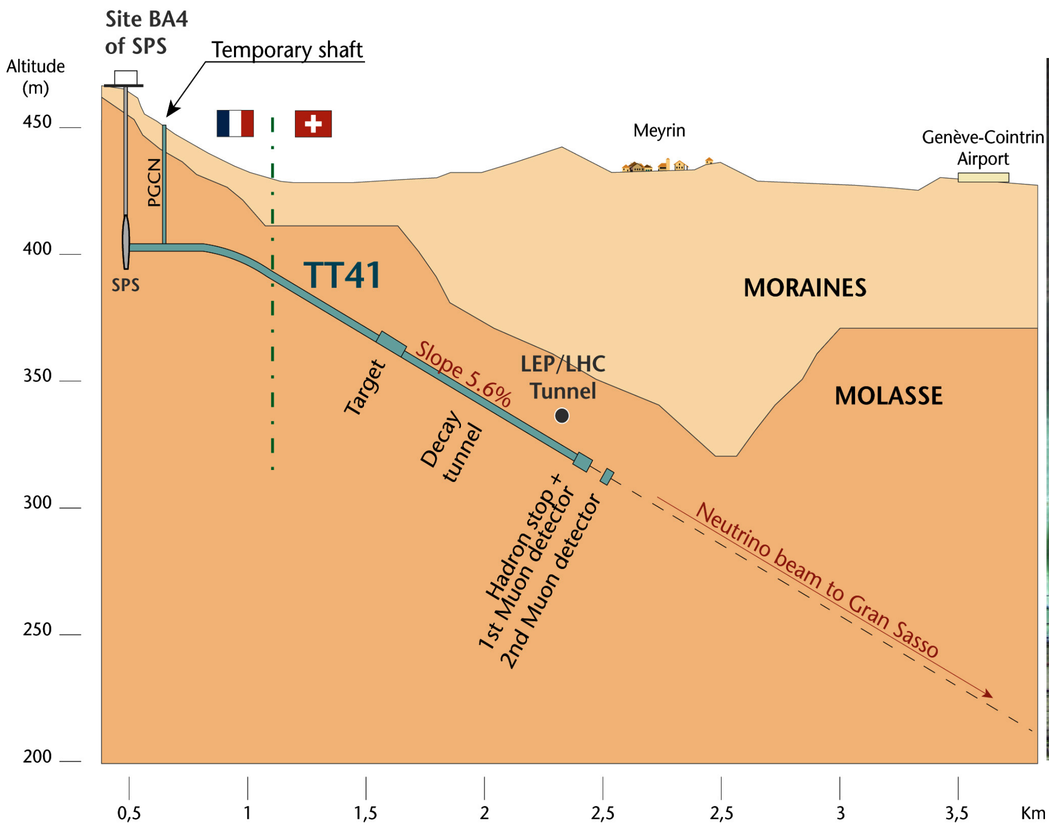
The beam

Beam composition : $97\%\,\nu_{\mu} + 2.1\%\,\bar{\nu}_{\mu} + 0.9\%\,\nu_{e}$

Neutrino energy $\langle E_{\nu} \rangle = 17\,\mathrm{GeV}$

Intensity: 4.5 10^{19}p.o.t/y $\Rightarrow$ 6.7 10^{19} p.o.t./y (+50% w.r.t. Proposal)

Baseline: 732 km



CNGS as a tool for $\nu_\mu \rightarrow \nu_e$ investigation

A beam tuned for tau appearance has:

- ✔ An energy not well tuned for $\nu_\mu \rightarrow \nu_e$ $(1.27\ \Delta m^2_{23}\ L/E \ll \pi/2)$
- ✔ No near detector
- ✔ Need very precise detectors (small mass)

However:

- ✔ Employs detectors with very high granularity (tau decay topology)
  1) Strong suppression of NC π^0 background
  2) Subtraction of $\nu_\mu \rightarrow \nu_\tau$
- ✔ Perform a "pure" $\sin^2 2\vartheta_{13}$ measurement

A pure measurement of $\sin^2 2\vartheta_{13}$

<u>CNGS is insensitive to the CP violating phase</u>

Suppressed by Δm^2_{12} $L/E_{CNGS} \ll \Delta m^2_{12}$ L/E_{MINOS}

If Δm^2_{12} big enough (i.e. $O(10^{-4})$) MINOS could see distortion of its appearance signal.

"Solar scale"

<u>CNGS is insensitive to matter effect</u>

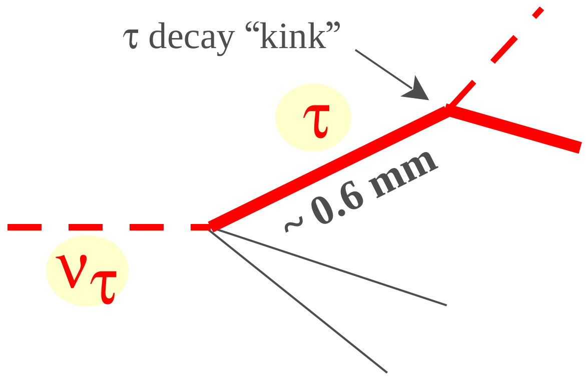
$$P(\nu_\mu \rightarrow \nu_e) = \frac{\sin^2 2\vartheta_{13}}{S^2} \sin^2\vartheta_{23} \sin^2 \frac{\Delta m^2_{23} L S}{4E} \simeq$$

$$\frac{\sin^2 2\vartheta_{13}}{\cancel{S^2}} \sin^2\vartheta_{23} \left(\frac{\Delta m^2_{23} L}{4E} \right)^2 \cancel{S^2}$$

In case of null result it would be difficult to put a limit on $\sin^2 2\vartheta_{13}$ due to our complete ignorance of δ and sign Δm^2_{23}

MINOS loose sensitivity with respect to CNGS

OPERA



An appearance experiment for tau detection on an **event−by event basis**

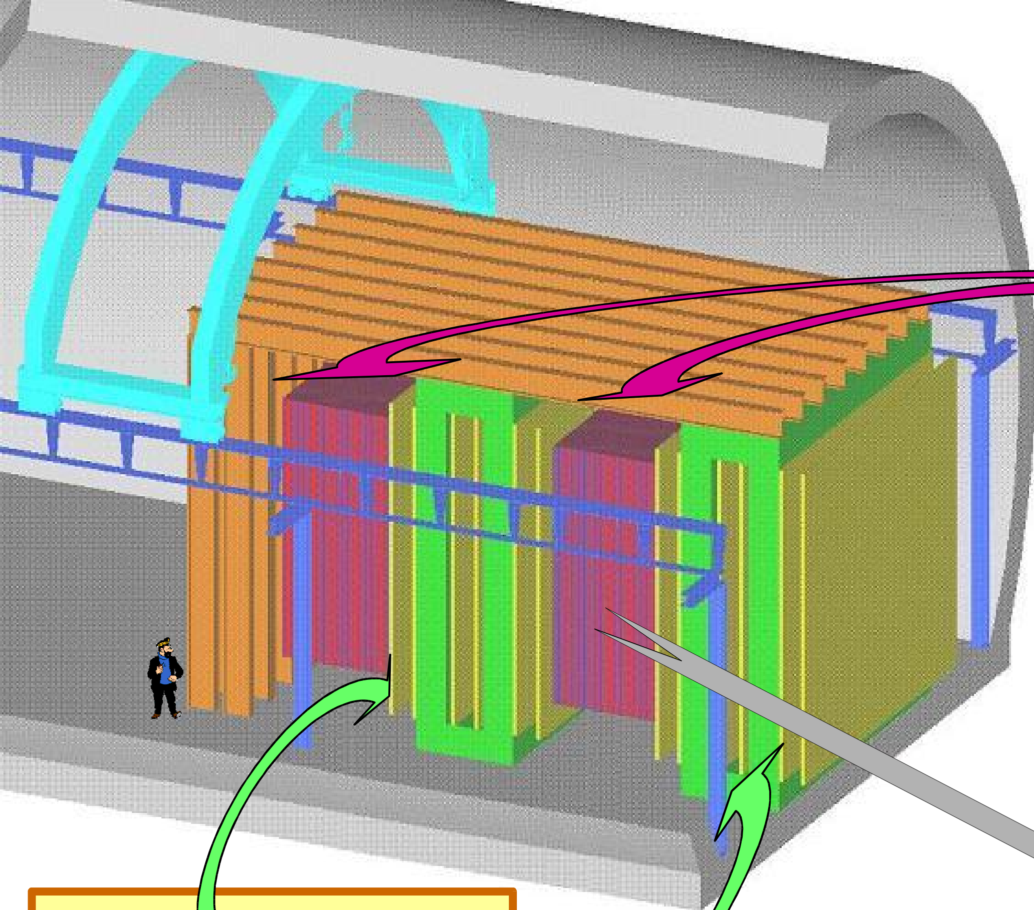
The cleanest channel to demonstrate $\nu_\mu \Rightarrow \nu_\tau$ oscillations

<u>BUT</u>

ν oscillation $\rightarrow$ huge mass **<u>AND</u>** τ decay $\rightarrow$ O(μm) resolution

Lead – nuclear emulsion sandwich

OPERA



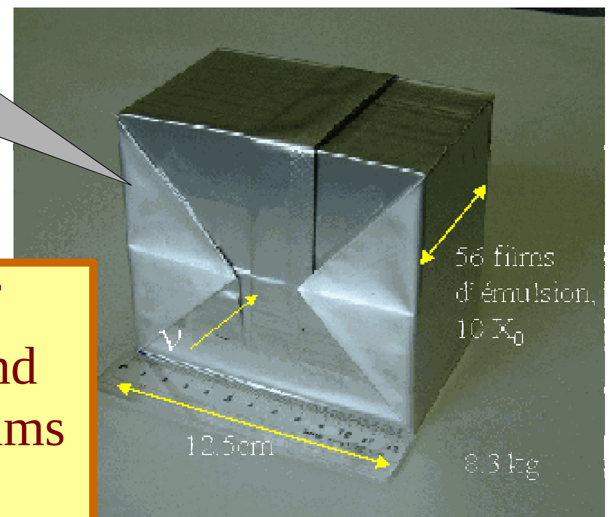
Target:

•**1.7kT of Lead** distributed in about **200 000 bricks**

•Trigger and brick finding from plastic scintillators.

•2 Spectrometers
- Dipoles
- RPC

Charge and momentum of penetrating particles



●sandwich” of 56 Pb sheets and 56 emulsion films

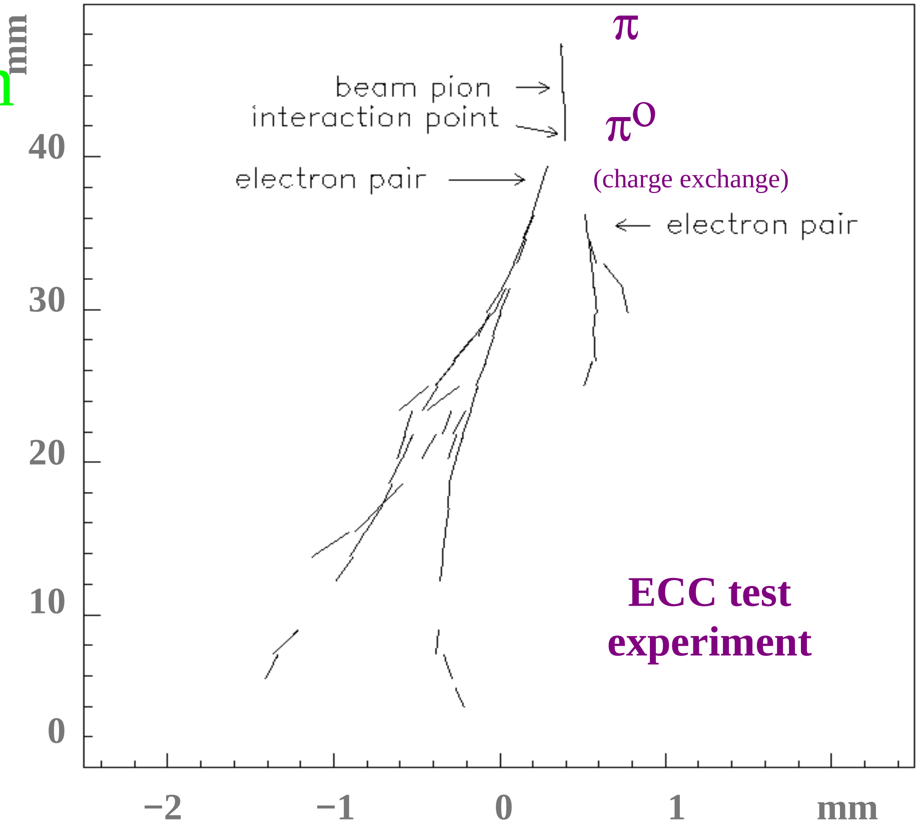
Background in OPERA

- NC events with π^0 production (high energy tail of ν_μ beam)

  as MINOS but eccellent 1mip/2mip separation by grain counting in emulsion + π^0 reconstruction

- CC events with π^0 production and primary μ unidentified

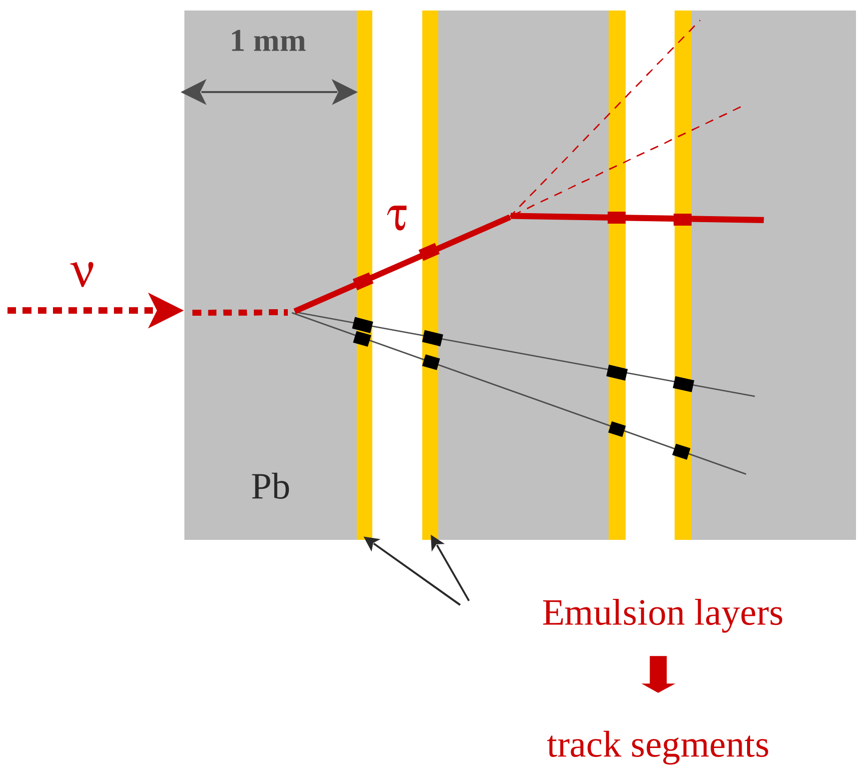
  suppressed by one order of magnitude w.r.t. NC



Background in OPERA

- ν_e contamination from the beam
  different energy spectrum

- $\nu_\mu \to \nu_\tau$ oscillation with $\tau \to e\nu\nu$
  kink observed on a event by event basis + low visible energy



Event selection

- Identified electron E>1 GeV (suppress low γ component)
- Kink below 20 mrad
  (against $\nu_\mu \rightarrow \nu_\tau$ oscillation with $\tau \rightarrow e\nu\nu$)
- E_{vis}<20 GeV (suppress ν_e contamination from the beam)
- Grain deposition near the vertex consistent with 1 m.i.p.
  (NC with π^0 suppression)
- P_t^{miss}<1.5 GeV (NC and $\tau \rightarrow e$ reduction)

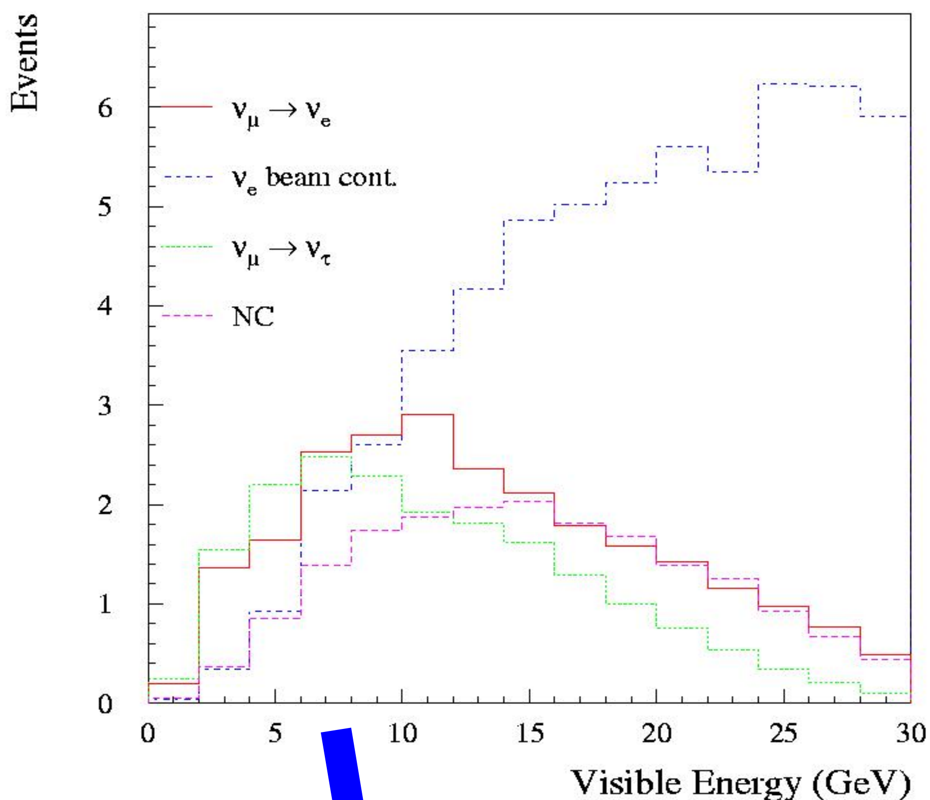
Scanning load

Scanning load is dominated by the vertex finding of neutrino interaction $\Rightarrow$ roughly unchanged w.r.t. the standard tau analysis

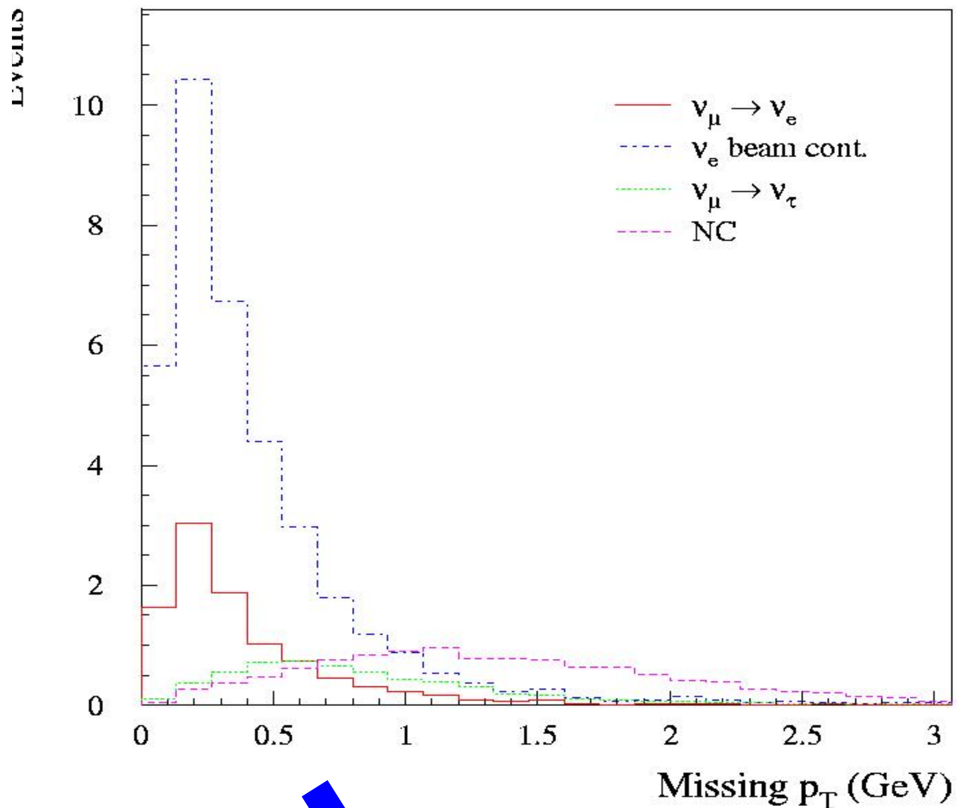
Kinematical analysis

(Δm^2=2.5 10^{-3} eV^2 ; $\sin^2 2\theta_{13}$=0.076 ; $\sin^2 2\theta_{23}$=1)

Visible energy



Missing p_T



Powerful ν_e CC (beam cont.) rejection

Powerful NC bkg. rejection

Expected events

5 years data taking with the nominal CNGS beam and

$\Delta m^2_{23}=2.5\times10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$

$\sin^2 2\theta_{13}$	θ_{13}	Signal	$\tau\rightarrow e$	ν_μCC	ν_μNC	ν_eCC beam
0.095	9°	9.3	4.5	1.0	5.2	18
0.076	8°	7.4	4.5	1.0	5.2	18
0.058	7°	5.8	4.6	1.0	5.2	18
0.030	5°	3.0	4.6	1.0	5.2	18
0.011	3°	1.2	4.7	1.0	5.2	18

OPERA is dominated by the intrinsic ν_e beam contamination. Here, we assume for consistency with other works a 5% error on the ν_e flux. However, given the small number of expected events in OPERA the sensitivity to θ_{13} is dominated by the statistical fluctuations of the background

A systematic error up to 10% does not change appreciably the experimental sensitivity

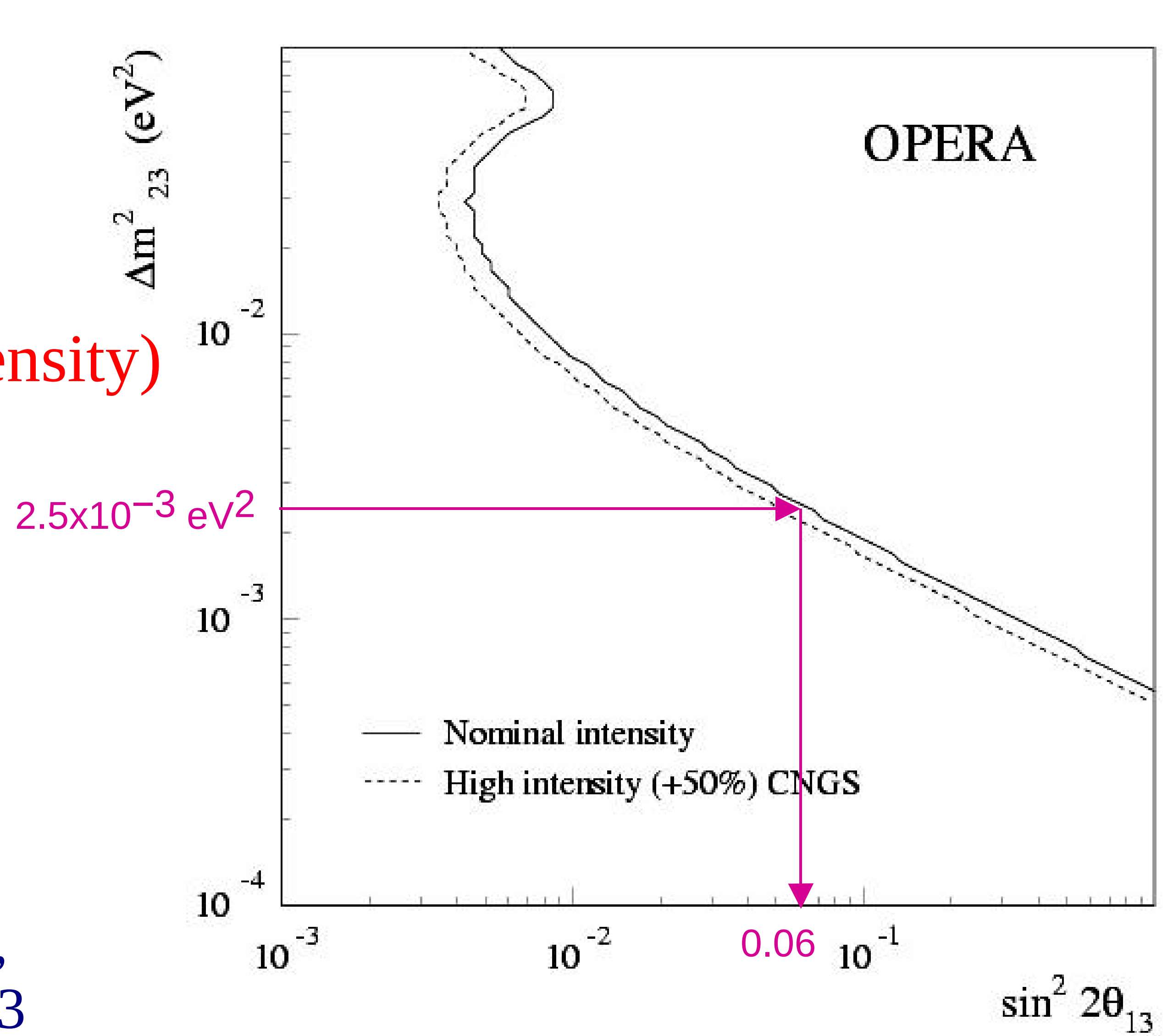
OPERA sensitivity to ϑ_{13}

By fitting simultaneously the E_e, missing p_T and E_{vis} distributions

$\Delta m^2_{23} = 0.025\ eV^2$

$\sin^2 2\vartheta_{13} < 0.06$ (old)

$\sin^2 2\vartheta_{13} < 0.05$ (new intensity)

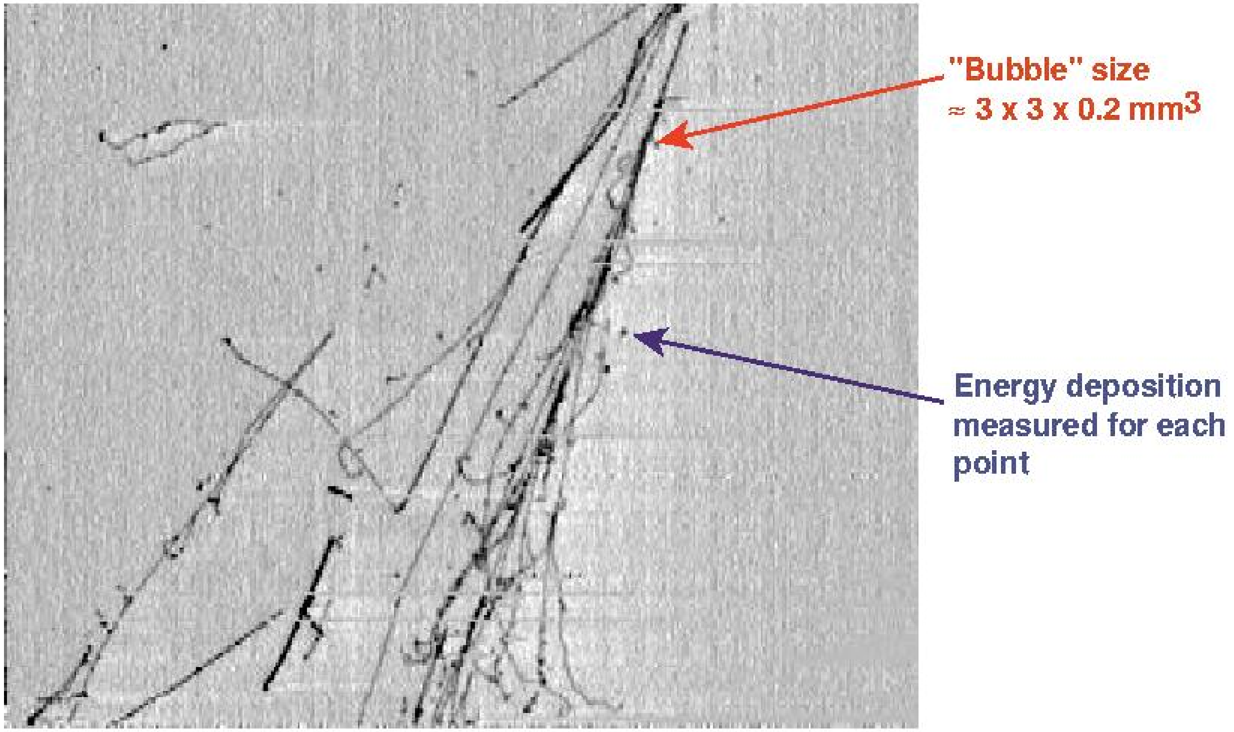


See M.Komatsu, P.Migliozzi, F.Terranova, hep−ph/0210043

ICARUS

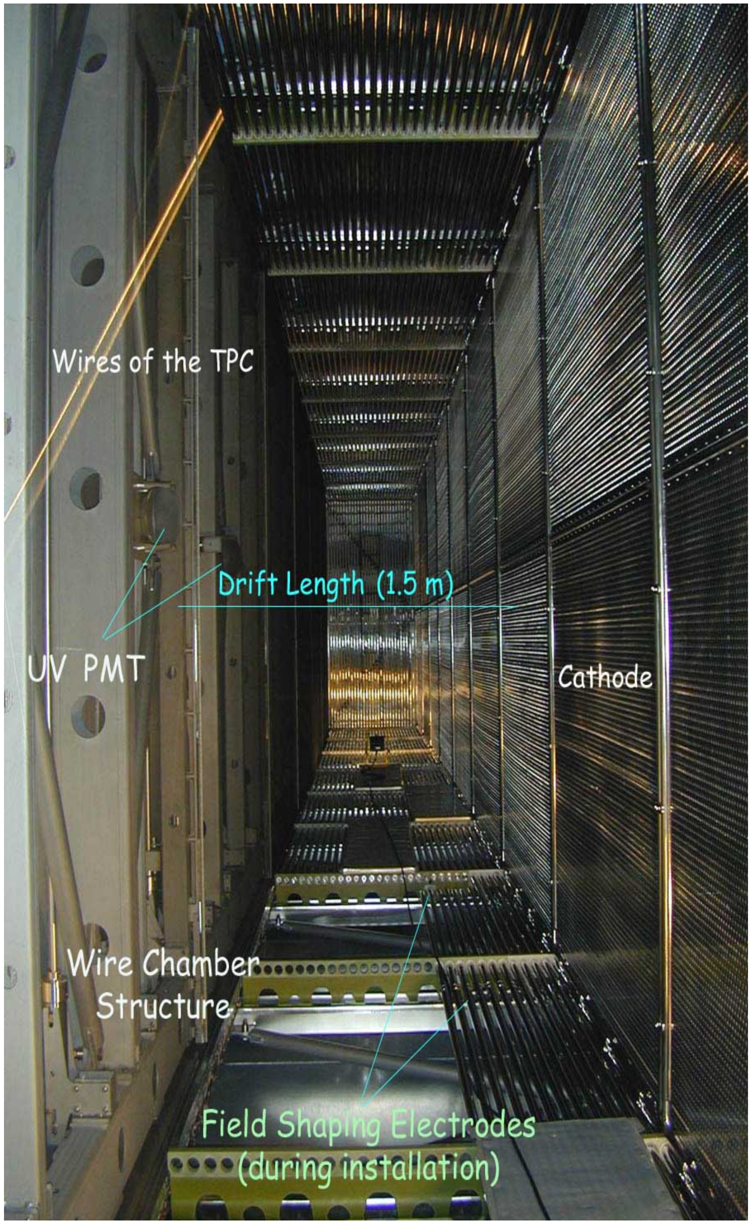
Technology based on Liquid Argon TPC

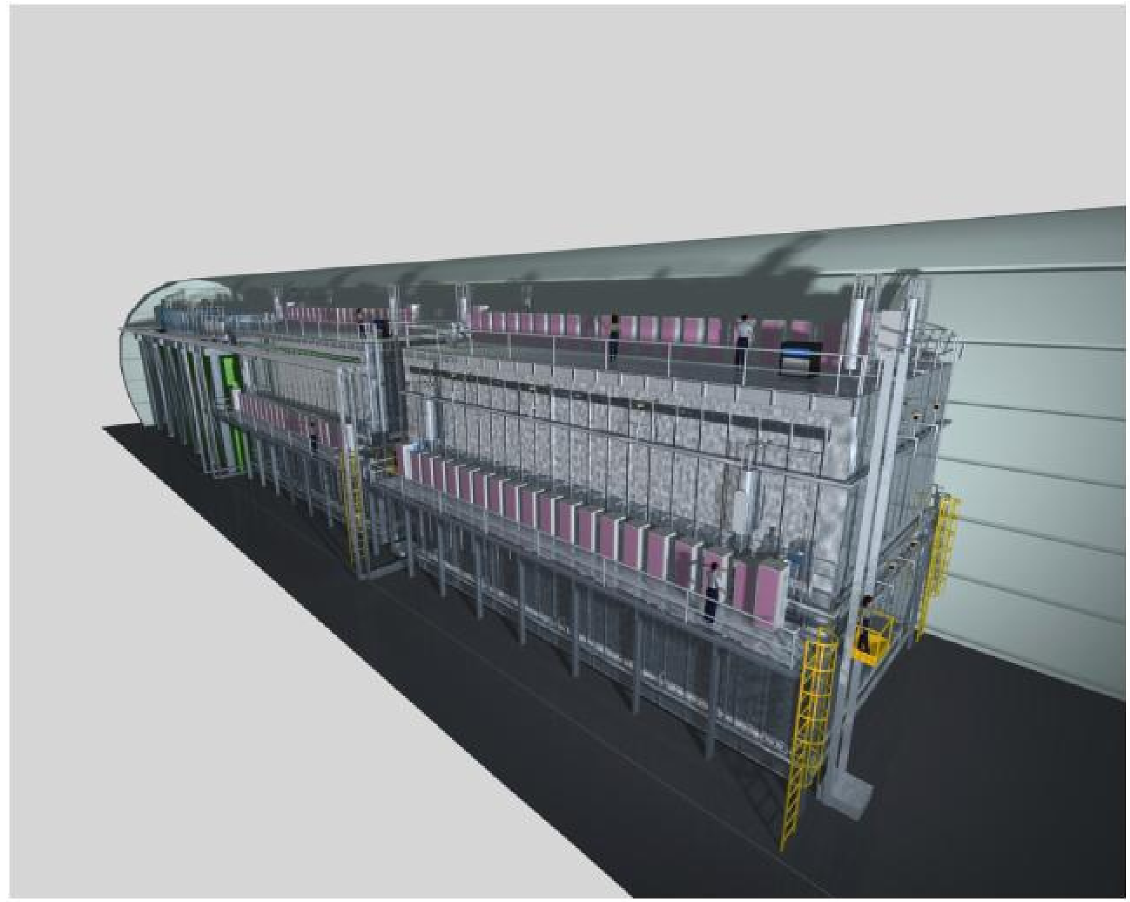
- High granularity depending on the drift time resolution and the induction wire pitch
- Electronic detector: no scanning time lag
- Calorimetric measurement: 3%/√E⊕1% (e.m.) ; 16%/√E⊕1% (hadr)



Construction and operation of big size detector has been recently demonstrated (600 tons)

A 2.4 kton detector in Gran Sasso Hall B could be ready for 2006





A different philosophy to see the τ

Granularity to poor to see the kink:

- Kinematical cuts to see distortion in the inclusive distribution of visible energy, lepton and hadronic p_T , missing energy etc.
- Liquid argon is much cheaper than Emulsion Cloud Chambers $\Rightarrow$ high mass detectors can be built

Limitation from poor granularity less dramatic for $\nu_\mu \rightarrow \nu_e$ search (kink finding is used only to anti−tag the $\nu_\mu \rightarrow \nu_\tau$ background)

Good detector for ν_e appearance

Background in ICARUS

- ν_e contamination from the beam

  different energy spectrum (the same problems as OPERA but with better energy resolution)
- $\nu_\mu \rightarrow \nu_\tau$ oscillation with $\tau \rightarrow e\nu\nu$

  kinematical cuts (less effective than OPERA kink−based suppression)
- NC events with π^0 production

  radiation length in Argon $\gg$ Lead : easier to see converted photon and employ a π^0/e separation procedure

Sensitivity per unit mass is approximately the same between ICARUS and OPERA when $\nu_\mu \rightarrow \nu_\tau$ is not the dominant background. However ICARUS has higher fiducial mass.

Expected events

5 years data taking with the nominal CNGS beam and
$\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1$

$\sin^2 2\theta_{13}$	θ_{13}	Signal	$\tau \to e$	$\nu_\mu CC$	$N\mu^{NC}$	$\nu_e CC$ beam
0.095	9^o	27	24	–	–	50
0.076	8^o	21	24	–	–	50
0.058	7^o	16	24	–	–	50
0.030	5^o	8.4	25	–	–	50
0.011	3^o	3.1	25	–	–	50

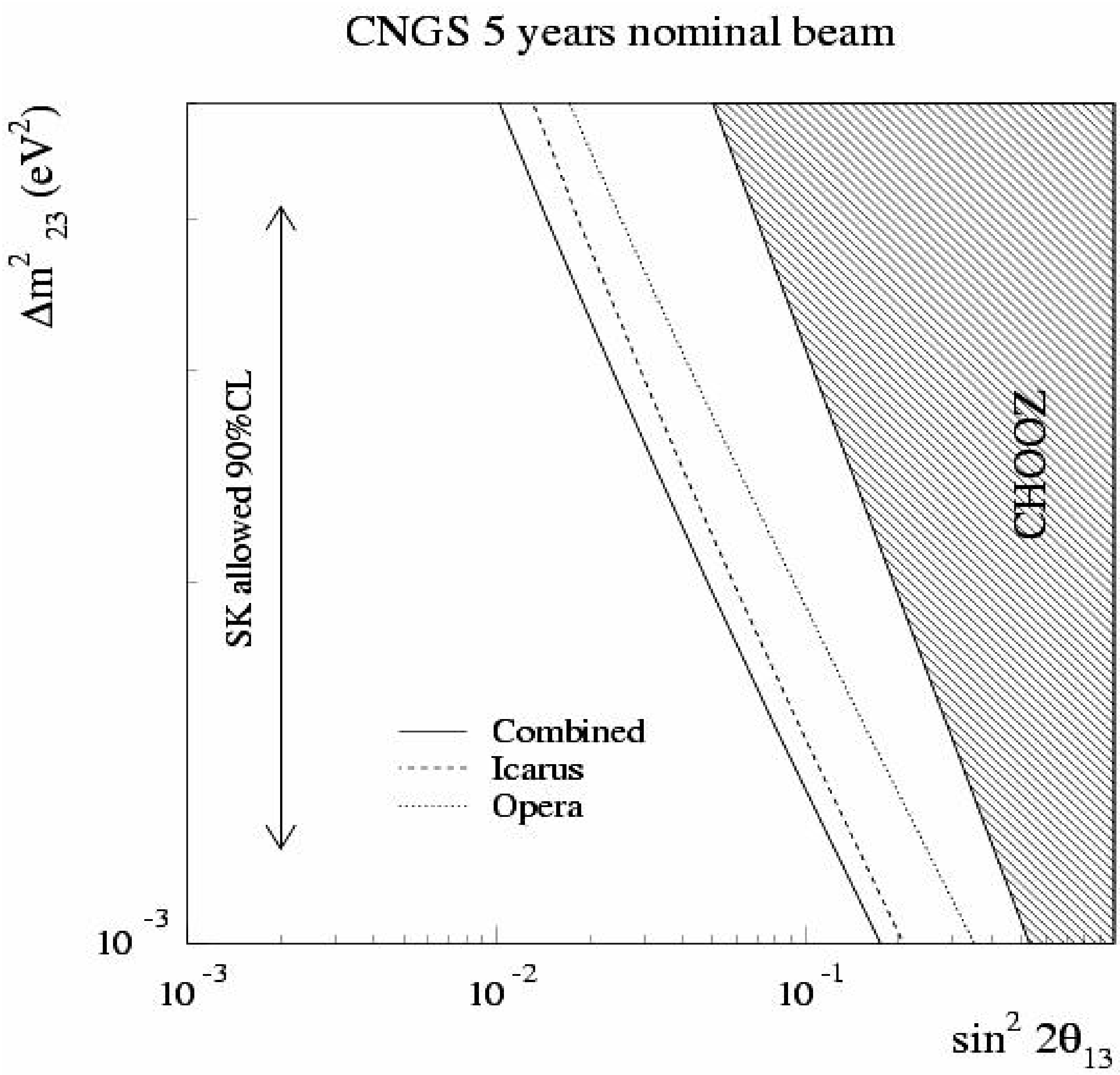
Including a kinematical analysis similar to the previous one (OPERA) we get

ICARUS 90% C.L. ; $\Delta m^2_{23} = 0.025$ eV^2

$\sin^2 2\vartheta_{13} < 0.04$ (old intensity)

$\sin^2 2\vartheta_{13} < 0.035$ (new intensity)

ICARUS and OPERA combined sensitivity



Comparing different scenarios

Limits at 90% C.L. on $\sin^2 2\theta_{13}$ and θ_{13}

($\Delta m^2_{23}=2.5\times10^{-3}$ eV^2; $\sin^2\theta_{23}=1$)

Experiment	$\sin^2 2\theta_{13}$	θ_{13}
CHOOZ	<0.14	<11°
MINOS 2yr	<0.06	<7.1°
ICARUS 5yr	<0.04	<5.8°
OPERA 5yr	<0.06	<7.1°
ICARUS+OPERA 5yr ≡3yr CNGSx1.5	<0.03	<5.0°
ICARUS+OPERA 5yr CNGS new intensity	<0.025	<4.5°
JHF 5yr	<0.006	<2.5°

Future projects

Low energy superbeams:

- Tune E and L to be at the oscillation maximum of Δm_{atm}
- Very high intensity beam ("superbeams")
- Near detector to lower systematics on beam contamination

JHF (E=1 GeV L=293 Km)
NUMI Off−axis (E=2 GeV L=800 Km)
BNL to Homestake (1<E<8 GeV L=2500 km)

Neutrino Factories

- Very pure $\bar{\nu}_\mu + \nu_e$ from μ^+ decays at muon storage rings
- High intensity beams to study $\bar{\nu}_e \to \bar{\nu}_\mu$ at Δm_{atm}
- Change of polarity (μ^- decays) to see CP odd asymmetries

JHF to Super−kamiokande

Main facility: JHF 50 GeV proton syncrotron. Deliver 10^{21} pot/y (about two order of magnitude higher than CNGS)

Detectors: near detector to be constructed (scintillator tracker). Far detector already there (Super−Kamiokande).

Phase I: JHF to SK will improve substantially the knowledge of ϑ_{13} and perform a precision measurement (1% level) of Δm_{23} and ϑ_{23}

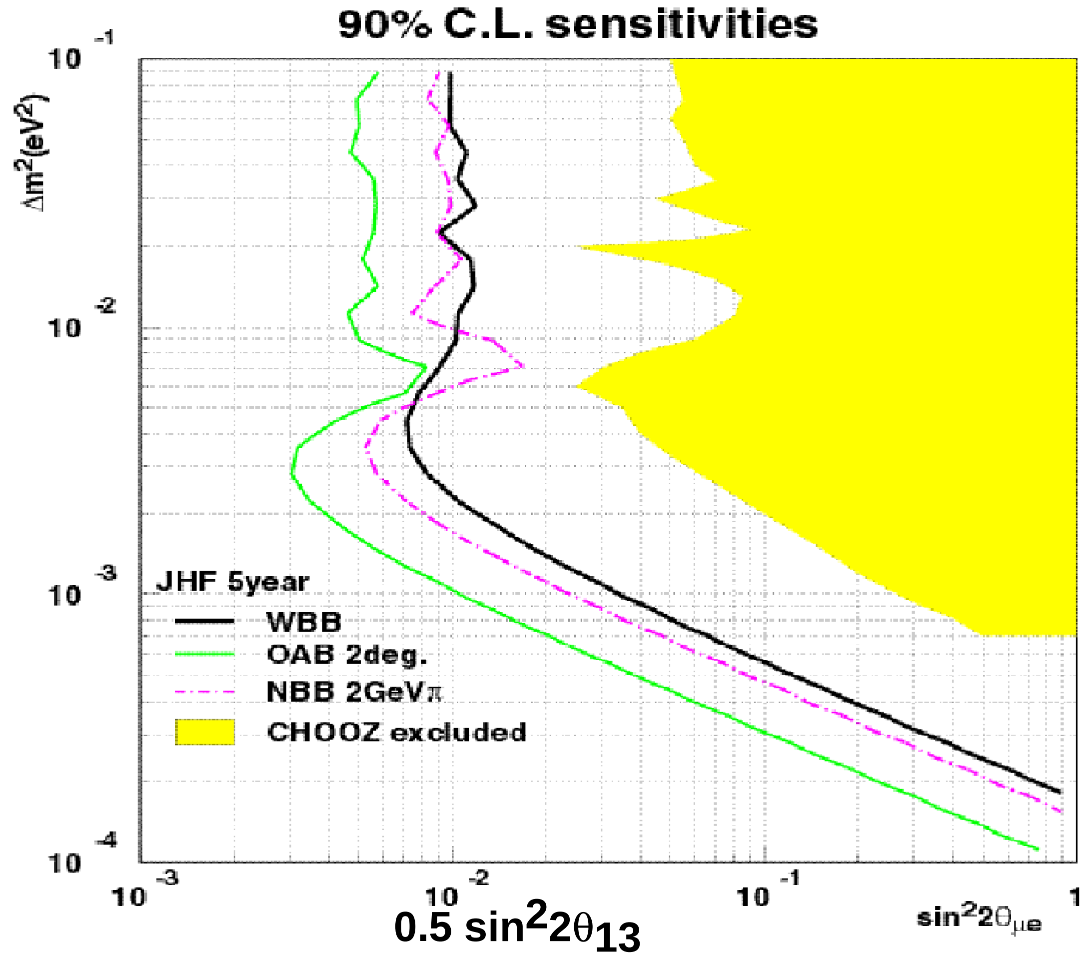
Phase II: Build a new huge detector (Hyper−K: 1Mton water) and further increase (x5) of beam intensity. CP violation in the leptonic sector

Sensitivity

Search for "single ring" e−like events in SuperKamiokande.

- Low ν_e beam contamination (0.3%)
- No tau background (below kinematic threshold)
- NC with single π^0 production $\Rightarrow$ low energy π^0 (γ back−to back)

JHF−SK 90% C.L.
$\Delta m^2_{23} = 0.025\ eV^2$
$\sin^2 2\vartheta_{13} < 0.006$



A note of caution!

If JHF−SK finds evidence of ν_e appearance: OK $\Rightarrow$ phase II + NuFact

<u>What if JHF−SK finds no evidence?</u>

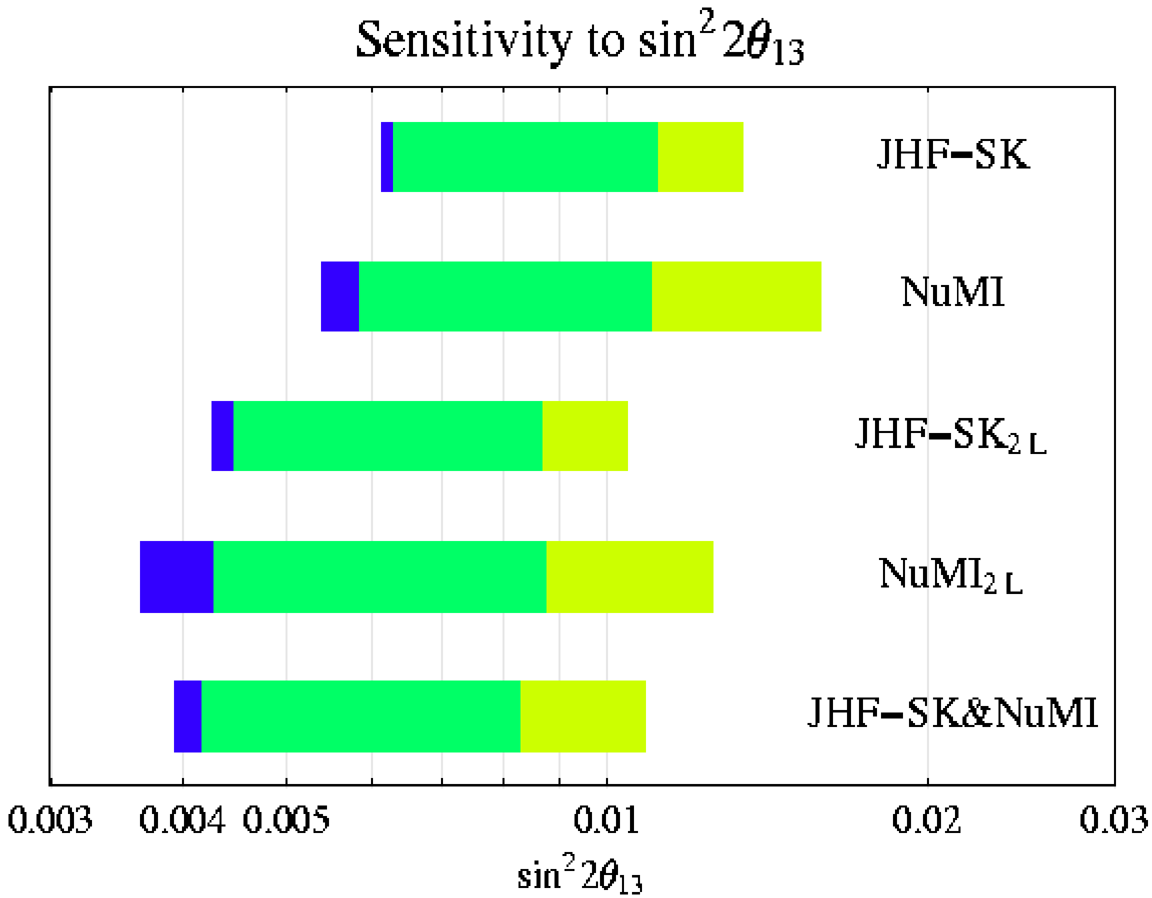
Can we say that $\sin^2 2\vartheta_{13}$ is too small and give−up phase II?

JHF−SK tuned to maximize discovery potential:

- Energy tuned to maximum of oscillation probability
- Enhance the dependence of subdominant terms to be sensitive to δ
- Small dependence on matter effect (low baseline). In NUMI Off−axis there is also this dependence

In case of no−signal one should integrate on all the subdominant parameters. Hence you could have high values of $\sin^2 2\vartheta_{13}$ still allowed $\Rightarrow$ deterioration of sensitivity

Sensitivity reduction



Assume Δm^2_{23}=3 10^{-3} eV^2 , $\sin^2 2\vartheta_{23}$ =1, Δm^2_{12}=5 10^{-5} eV^2

See P.Huber, M.Lindner, W.Winter, hep−ph/0211300

My own opinion...

This problem affects MINOS as well but **not** CNGS!!

CP violating phase:

Terms suppressed by $[\Delta m^2_{12} L/E]^2$ (solar scale) but $E_{minos} \approx 0.1 E_{CNGS}$

At CNGS further suppressed

Matter effect:

once more, being not at the oscillation max, the effect is suppressed (see before). CNGS doesn't care of the sign of Δm^2_{23}

The (ϑ_{23} , $\pi/2-\vartheta_{23}$) degeneracy:

This affect also CNGS (irrelevant if maximal mixing, $\vartheta_{23}=\pi/4$)

CNGS makes a pure ϑ_{13} measurement and,

in this respect, it has a sensitivity comparable to JHF!!

Next generation superbeams should be tuned in a smarter way...

or we should stick on reactor experiments

Conclusions

- The knowledge of the parameter driving the sub−dominant mixing between atmospheric and solar neutrinos (ϑ_{13}) is the missing piece to start precision physics of the leptonic CKM matrix

- MINOS and CNGS can provide already a significant improvement w.r.t. CHOOZ

- The standard strategy
  MINOS/CNGS $\Rightarrow$ JHF phase I $\Rightarrow$ JHF phase II
  could be not the optimal one