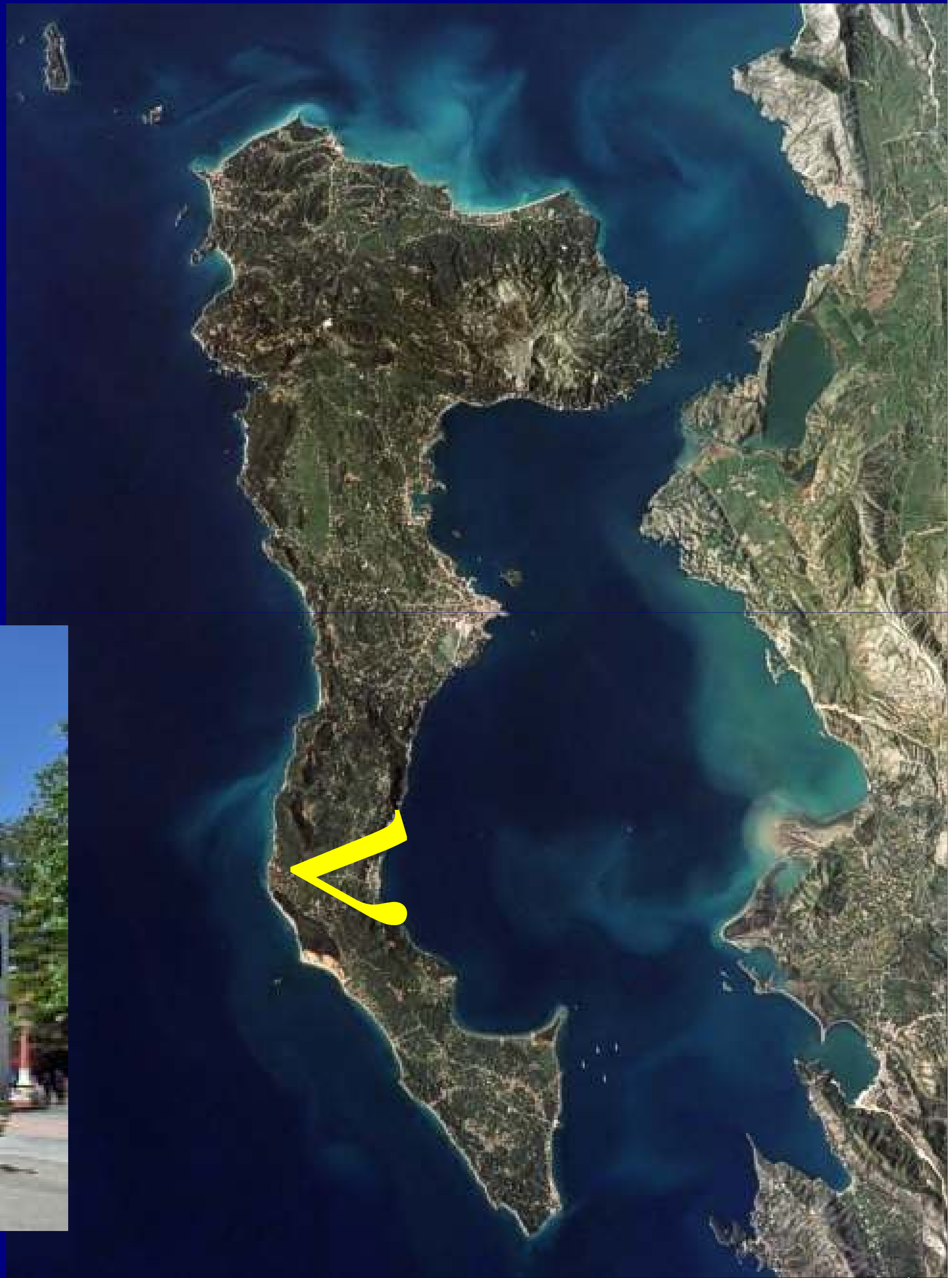
Corfu 2015
Summer School and Workshop on the Standard Model and Beyond

10/9/2015

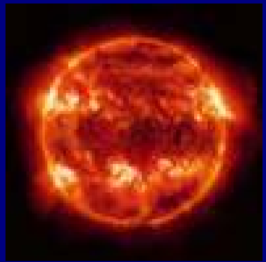
Experimental Neutrino Physics

D. Autiero (IPNL Lyon)



Neutrino sources:

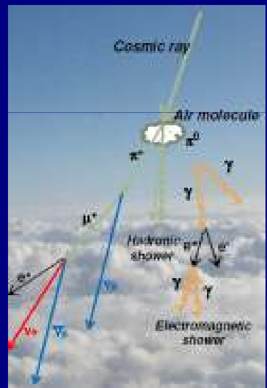
Supernova
explosion
99% of collapse
energy in neutrinos
10-30 MeV



Sun:
65 billions/s/cm2
on the earth surface
~ MeV

Earth radioactivity
U, Th, K
→Geoneutrinos
4E6 /(cm2 s)
~ MeV

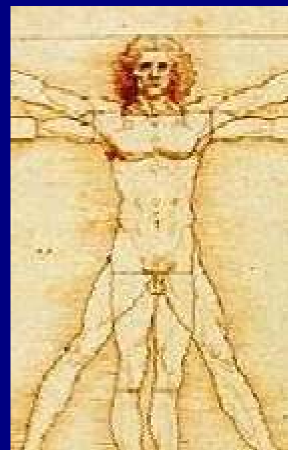
Nuclear reactors:
1 GW → 2E20 anti-nue/s
~ few MeV



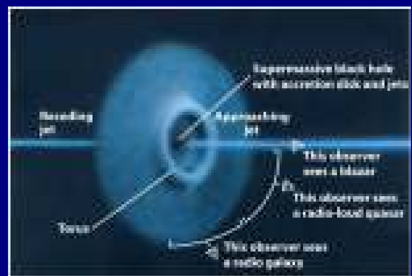
Cosmic rays
~ GeV
~ 1 / (cm2 minute)

Big Bang
Relic neutrinos
330/cm3
1.95 K

Human body
20 mg of K 40
340 millions/day



Particle accelerators
~few GeV



Extragalactic:
Active galactic nuclei
Gamma ray bursts
~PeV

At this school you had already very nice theoretical introductions on neutrinos, I do not have to convince you that neutrinos are very interesting particles:

- Cosmology:

They played an important role during the Big Bang, they could explain the asymmetry among matter and anti-matter, they are the most abundant form of matter in the universe

- Astrophysics:

They are governing the life and death of stars

- Particle Physics:

They are a window on physics beyond the Standard Model: presently they represent the only experimental hint in that direction

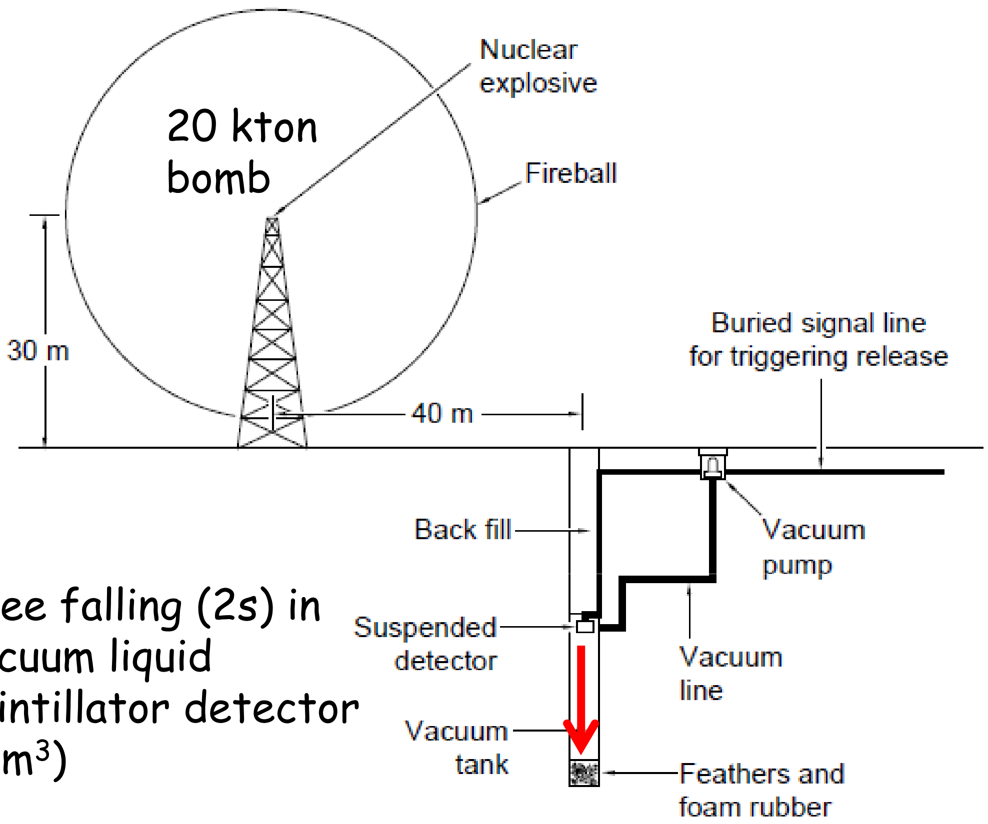
Unfortunately neutrinos are also quite difficult to detect, requiring bright ideas on sources and detectors. This lecture concerns the "Experimental challenges" and also a little bit of history, many neutrino properties were totally unexpected coming out as experimental results:
→ The history of neutrino physics is a real saga with an <u>extraordinary richness of experimental techniques</u> involved related to the various neutrino sources, There are still a lot of open questions in neutrino physics …

Experiments with solar neutrinos
Experiments with atmospheric neutrinos
Experiments with reactor neutrinos
Experiments with accelerator neutrinos short/long baseline
Direct neutrino mass measurements
Searches for neutrinoless double beta decay
Cosmological measurements
Etc …

It is impossible to cover all that
In one hour !

This lecture will be partial and biased on some aspects more related to the study of neutrino oscillations at accelerators

How to detect neutrinos by producing them in a nuclear explosion:



Free falling (2s) in vacuum liquid scintillator detector (1 m^3)

Figure 1. Detecting Neutrinos from a Nuclear Explosion
Antineutrinos from the fireball of a nuclear device would impinge on a liquid scintillation detector suspended in the hole dug below ground at a distance of about 40 meters from the 30-meter-high tower. In the original scheme of Reines and Cowan, the antineutrinos would induce inverse beta decay, and the detector would record the positrons produced in that process. This figure was redrawn courtesy of Smithsonian Institution.

« El Monstro »
Reines and Cowan 1951-1952
Approved after discussing with Fermi and Bethe who were convinced that this was the most promising (anti)neutrino source

- ✓ Intense
- ✓ Short flash (less environmental background)

but then abandoned in favor of the detection at a nuclear reactor:

Bomb: flux ~10^E4 times larger than with a reactor

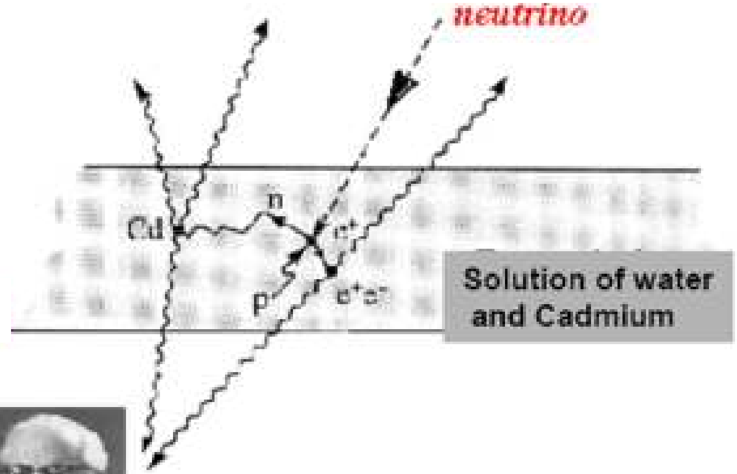
Background from neutrons and gammas similar to reactor

→ But a new idea on how to reduce the background and detect neutrinos over a long time scale with the low reactor flux

1956 (anti)neutrino detection at the Savannah River reactor, still via inverse beta decay

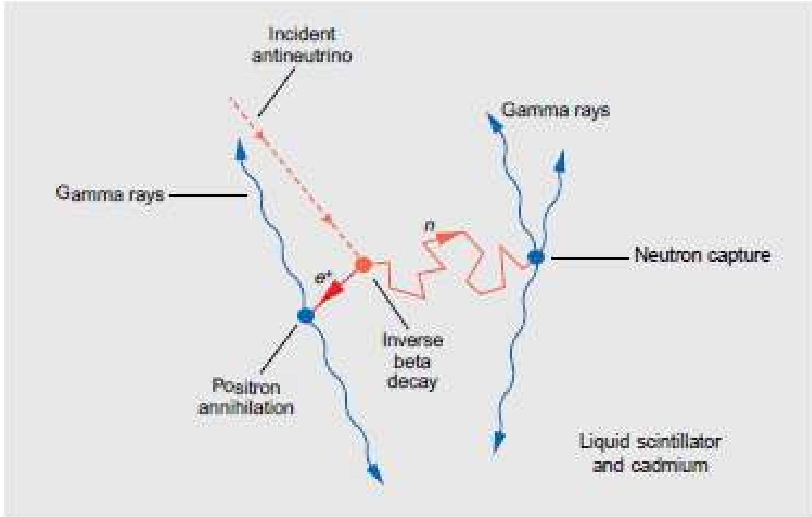
flux ~10^{E}13 neutrino / (cm2 s)

the idea to reduce the background: detect also the delayed neutron capture signal after the positron →

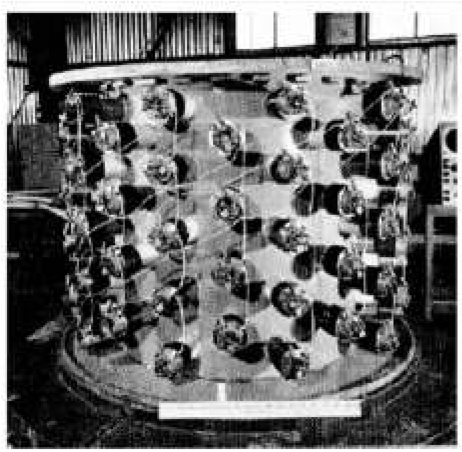


Reines: 1995 Nobel Prize

Reines:
« We are happy to inform you (Pauli) that we have definitely detected the neutrino ! »



Detector 12 m underground
and 11 m from reactor
~3 neutrinos detected/hour



First detection of solar neutrinos 1968: Homestake mine experiment (R. Davis)
Depth equivalent to 4100 m of water

$\nu + {}^{37}Cl \rightarrow \beta^- + {}^{37}Ar$, ${}^{37}Ar \rightarrow {}^{37}Cl$ (34 days, K-capture) $e^- + {}^{37}Ar \rightarrow \nu_e + {}^{37}Cl$

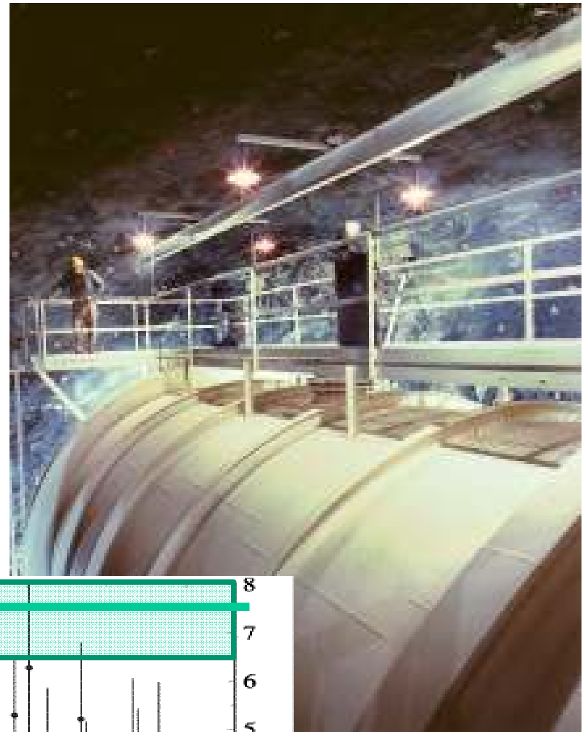
E(neutrino)> 0.814 MeV

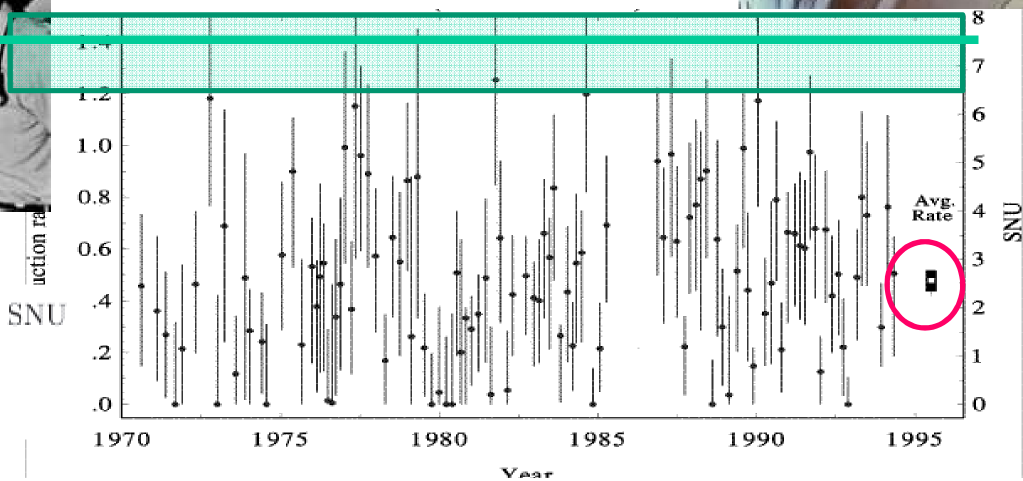
Tank with 390 **m**^{3} of **C_2Cl_4**
^{37}Cl ~24% of natural Cl

~1.5 Ar atoms/day produced by solar neutrinos
Extracted every 3 months with a flux of N_2

Final state ^{37}Cl excited emitting Augier electrons e/o x rays

Results compared to the neutrino flux predicted by the Standard Solar Model (J. Bahcall)





→ 1/3 of expected rate
Solar neutrinos deficit

$$R({}^{37}Cl) = 2.56 \pm 0.16 \pm 0.16 \text{ SNU}$$
$$R_{SSM} = 7.6^{+1.3}_{-1.1} \text{ SNU}$$
$$R_{Données/SSM} = 0.33 \pm 0.03$$

Interpretations:

I [J.N. Bahcall] want to tell you an illustrative story about neutrino research ... One of the miners came over to our bench, said : "Hello, Dr. Davis. How is it going ? You don't look too happy." And, Ray replied : "Well, I don't know ...I am capturing in my tank many fewer of those neutrinos than this young man says I should be capturing." The miner [...] finally said : "Never mind, Dr. Davis, it has been a very cloudy summer here in South Dakota. "

More seriously debated for long … long time:

The trivial ones:

- The Homestake experiment, which is quite delicate, has some bias in the neutrino detection
- The Standard Solar Model is not correct

The fascinating one by Pontecorvo:
the Davis experiment and the SSM are both correct it is new physics: neutrinos change their nature during their trip to the earth

→ Neutrino oscillations
Electronic neutrinos from the sun become muonic neutrinos
The energy of the muonic neutrinos is too low to allow for their charged current interactions → neutrino disappearance

But neutrinos must be massive particles …

ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

JOINT INSTITUTE FOR NUCLEAR RESEARCH

Москва, Главный почтамт п/я 79. Head Post Office, P.O. Box 79, Moscow, USSR

№ 994/31 April 6/10 19 72

April 6, 1972

Prof. J.N.Bahcall

The Institute for Advanced Study
School of Natural Science
Princeton, New Jersey 08540, USA

Pontecorvo was predictive:
It took 30 years for the demonstration !

Dear Prof. Bahcall,

Thank you very much for your letter and the abstract of the new Davis investigation the numerical results of which I did not know. It starts to be really interesting! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately, it will not be easy to demonstrate this, even if nature works that way.

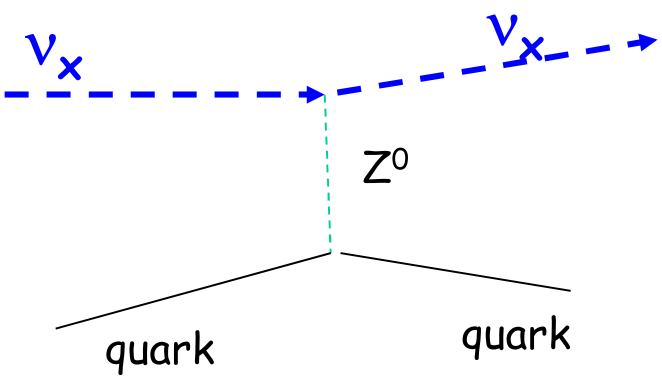
I will attend the Balaton meeting on neutrinos and looking forward to see you there.

Yours sincerely,

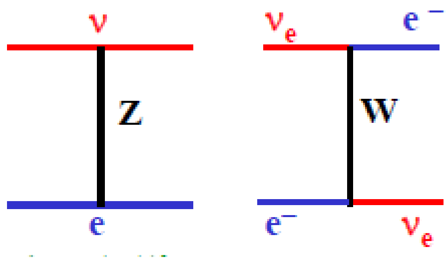
B Pontecorvo

B.Pontecorvo

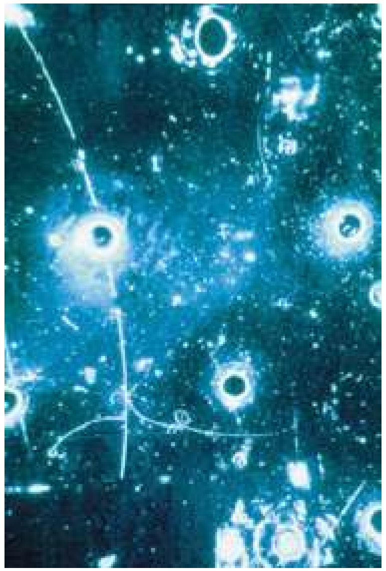
Neutral current reactions (Z exchange), do not distinguish neutrinos, no threshold



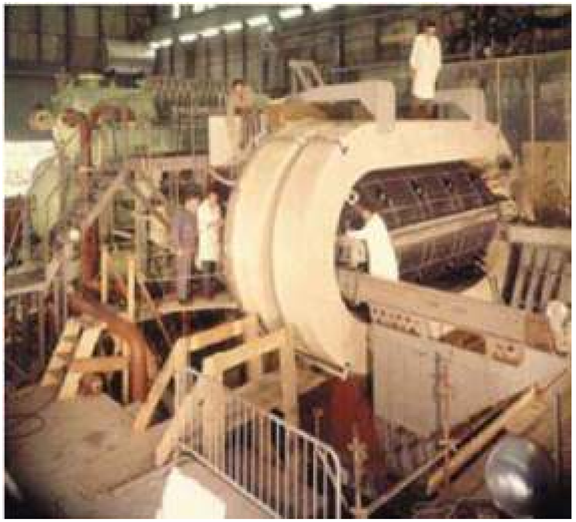
Elastic scattering neutrino-electron



Discovery of neutral currents 1973 (10 years before the discovery of the Z)

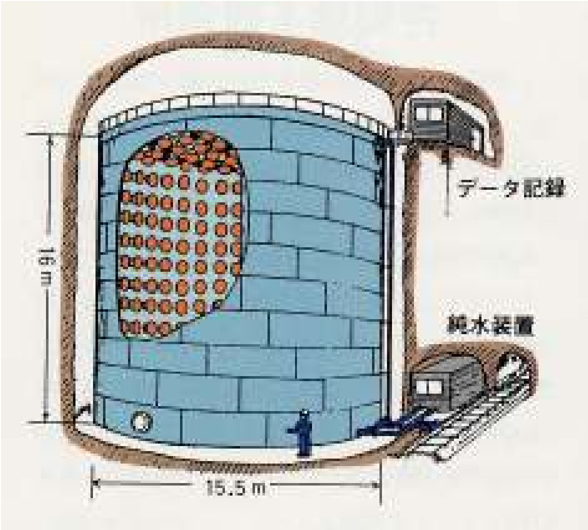


Bubble chamber experiment Gargamelle



Bubble chambers are a sort of reference in neutrino physics acting as homogeneous neutrino target and allowing for a precise imaging and measurement of final state particles
→ We will discuss in the next slides their modern versions

Water Cerenkov experiment (Kamiokande 1987-1994)

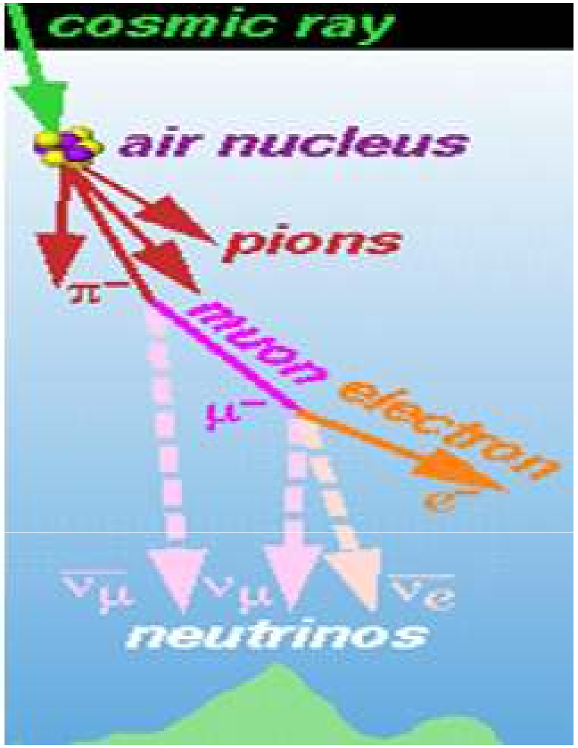


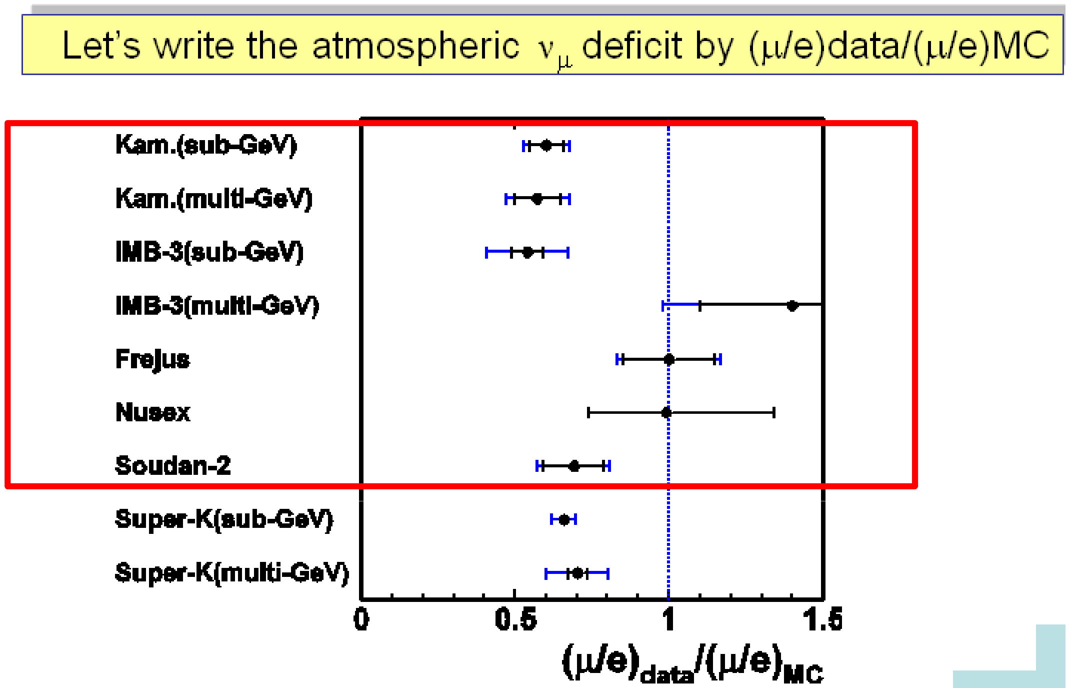
Particle detection by emission of Cerenkov light in water (680 tons) → (electrons, muons)

Built for proton decay search
Neutrinos produced by cosmic rays in the atmosphere are a background for cosmic rays
→ Studying this background people realize that it is different than expectations

→ Can look at solar neutrinos (high threshold > 5 MeV) by elastic scattering on electrons (emitted electron at 5 MeV stops in ~2 cm in water)
→ Deficit of solar neutrinos ~50%

Atmospheric neutrinos anomaly





Unclear situation among different experiments (WC, Calorimeters)
Interpretation in terms of neutrino oscillations (possible in terms of both $\nu\mu \rightarrow \nu e$ and $\nu\mu \rightarrow \nu\tau$) with $\Delta m^2 \sim 10^{-2}$ eV^2

Some first hints of dependence on the zenith angle but not yet convincing

Neutrino oscillation searches at the beginning of 90s

- The long standing (since 1968) problem of the solar neutrino deficit opened by the Homestake measurements (+ Kamiokande since 1986)

In 1992 first Gallex results confirm the deficit also for neutrinos from the pp cycle

- Atmospheric neutrino anomaly still quite weak

The controlled observation of neutrino oscillations with an accelerator neutrino beam would have been a great discovery, where to search ?

Prejudice towards small mixing angles and large Δm^2

✓Take the MSW solution of the solar neutrino deficit: $\Delta m^2_{\mu e} \sim 10^{-5}$ eV^2

✓Assume a strong hierarchy: $m_{\nu e} \ll m_{\nu\mu} \ll m_{\nu\tau} \rightarrow m_{\nu\mu} \sim 3\times10^{-3}$ eV

✓Assume the See-Saw mechanism: $m(\nu_i)=m^2(f_i)/M$
M=very large Majorana mass $m(f_i)$= e.g. quark masses

Then: $m_{\nu\tau} \sim 30$ eV (Cosmological relevance)

« ν are an important component of the dark matter » ~ a few 10 eV
Harari PLB 1989

With $m_{\nu\tau}$ ~ 30 eV cosmological neutrinos important component of dark matter $\Delta m^2_{\mu\tau}$ O(100 eV^2)

Look for $\nu_\mu \rightarrow \nu_\tau$ with short baseline experiments at accelerators, high energy beam

CERN ν_τ appearance experiments:

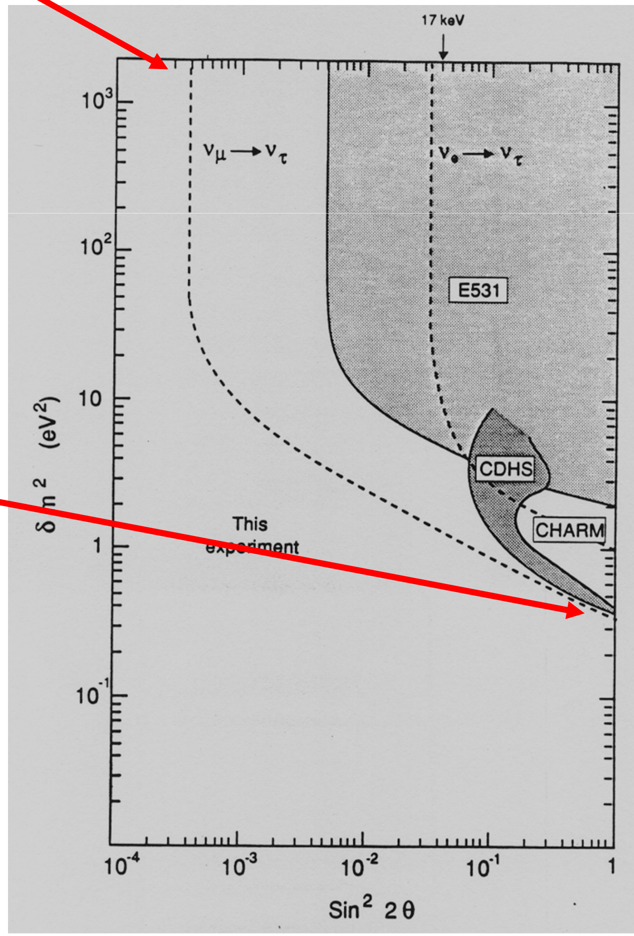
sensitive down to:

$P_{\mu\tau}$~ 1.5x10^{-4} (90% CL) **(x10) improvement**

Search for ν_τ appearance from oscillations in the CERN wide band neutrino beam (WANF)

Pioneers of the technique also for long baseline experiments, important samples of neutrino interactions well measured

<E_ν>=24 GeV
<L>=600 m
sensitive to:
1 eV^2 < Δm^2



NOMAD:
- Proposal 1991
- Detector 1995
- Data-taking 95-98 (1.35 M ν_μ CC)

CHORUS:
Data-taking 1994-1997 (0.71 M ν_μ CC)

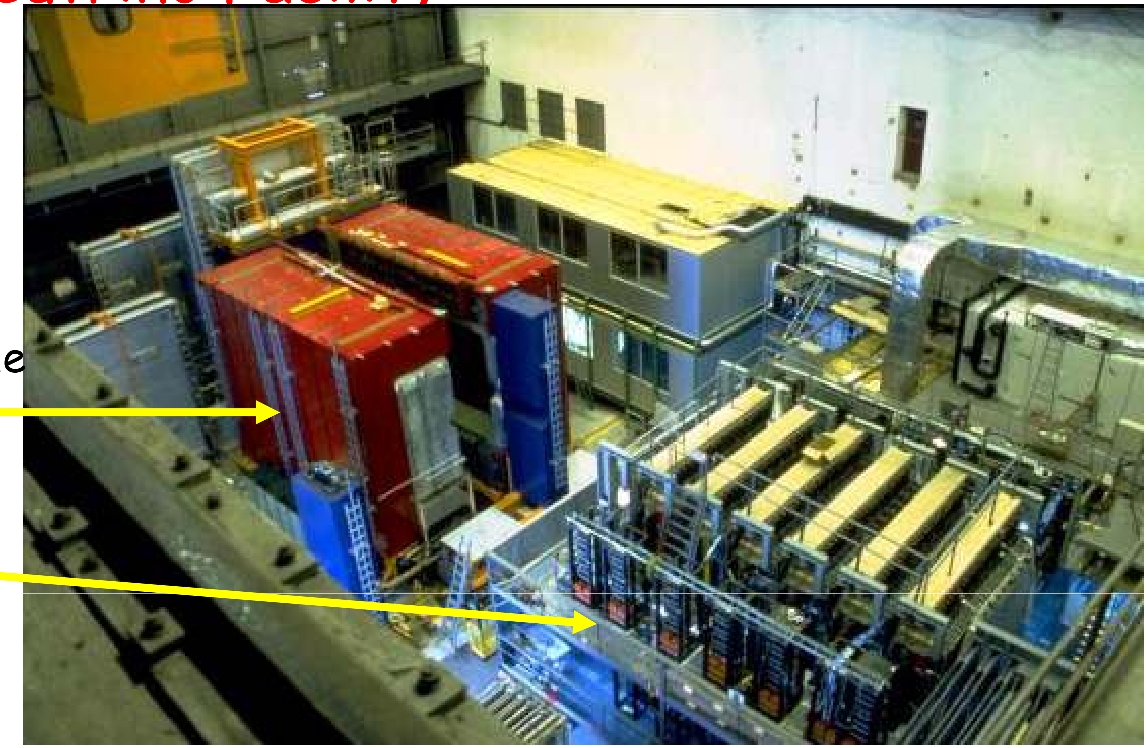
The NOMAD/CHORUS experiments at the CERN West Area Neutrino Facility

Short-baseline search for
$\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ oscillations

Running in 1994-1998

The NOMAD experiment hosted in the UA1/NOMAD/T2K magnet

The CHORUS experiment



NOMAD: measurement of τ decay kinematics:

Presence of neutrino(s) in the final state, missing P_t , visible decay daughters
→ (tracking, calorimetry) → main channel: electronic tau decay

Collected samples:
1.3 M $\nu\mu$ CC
0.4 M $\nu\mu$ NC
13 K νe CC

τ decay modes

$\mu\bar{\nu}_\mu\nu_\tau$	17.4%
$e\bar{\nu}_e\nu_\tau$	17.8%
$h(n\pi^0)\nu_\tau$	49.8%
$3h(n\pi^0)\nu_\tau$	15.2%

Exploit the small νe background (~1%):
τ->e channel: electron id

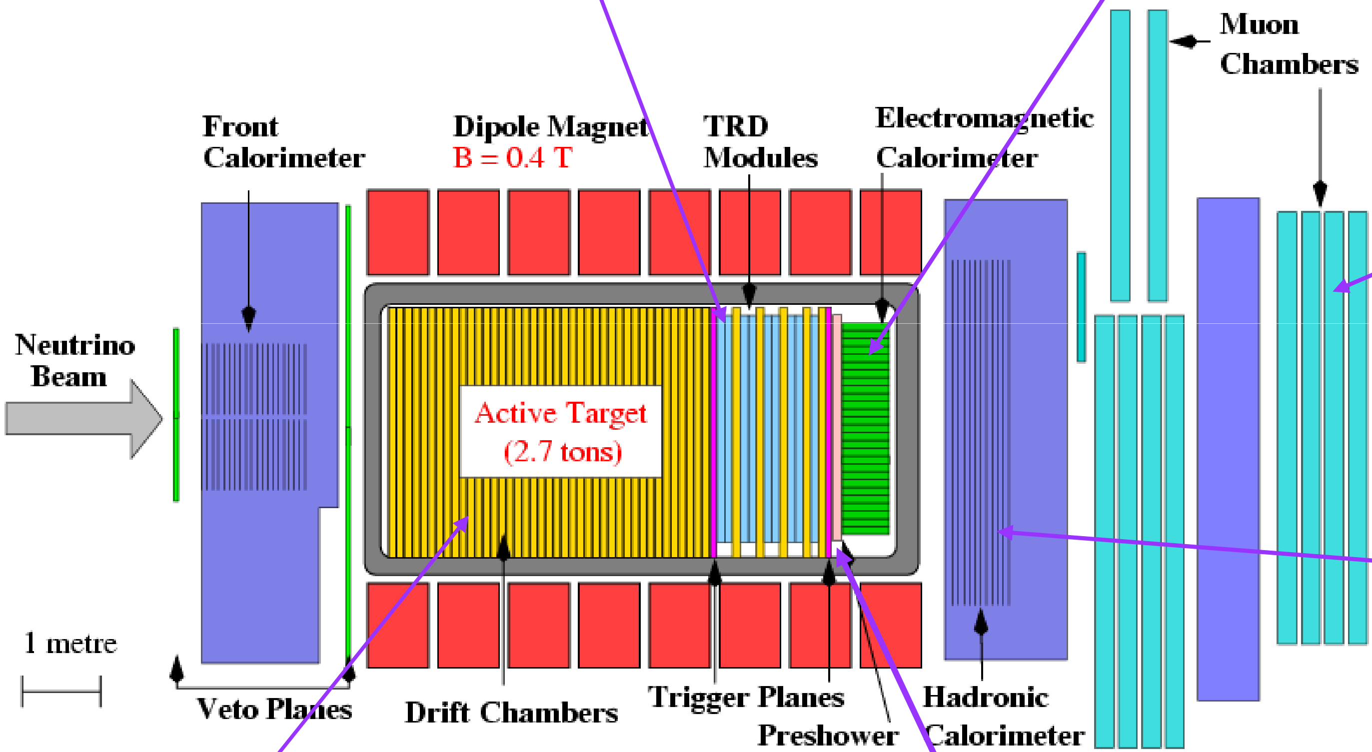
Go down to $P_{\mu\tau}$~ 10^{-4}

The NOMAD detector

Transition Radiation Detector (TRD) (e identification)
9 modules (315 radiator foils followed by straw tubes plane) π rejection ~ 10^3 for electron efficiency > 90%

Lead glass electromagnetic Calorimeter (measurement of energy and position of e.m. shower)

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus 1\%$$



Muon Chambers (μ identification)
ε~ 97% for p_μ > 5 GeV/c

Hadronic calorimeter (n and k^0_L veto)

Drift chambers (target and momentum measurement) Fiducial mass 2.7 tons with average density 0.1 g/cm³ 44 chamber + 5 chambers in TRD region, momentum resolution 3.5% ~ (p < 10 GeV/C)

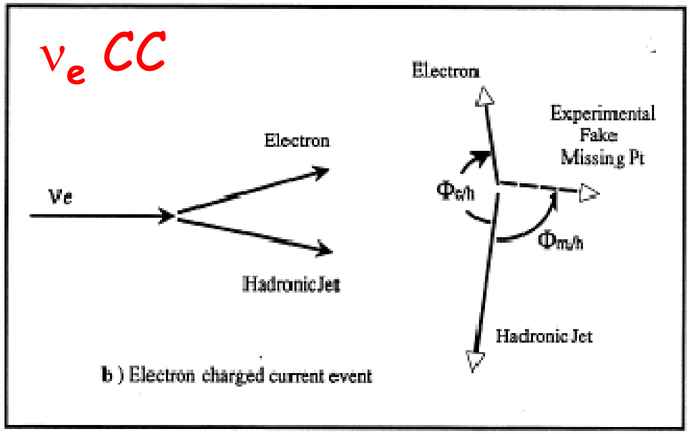
Preshower (e and γ detection) additional π rejection ~ 10^2 for electron efficiency > 90% precise γ position measurement $\sigma(x)$, $\sigma(y)$ ~ 1cm

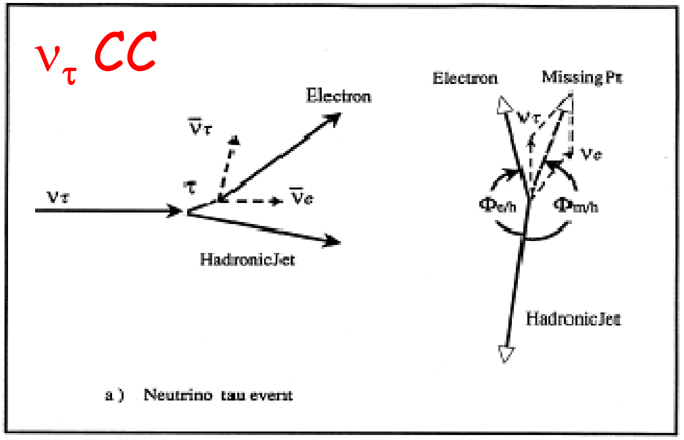
Use of kinematics to extract a ν_τ signal:

(First proposed by Albrigth and Shrock P.L.B. 1979)

NOMAD: fully reconstruct 1.7 M neutrino interactions, with good resolution, at single particles level:

→ Kinematics closure on the transverse plane





Find ντ down to $P_{\mu\tau} \sim 10^{-4}$ in a large background:

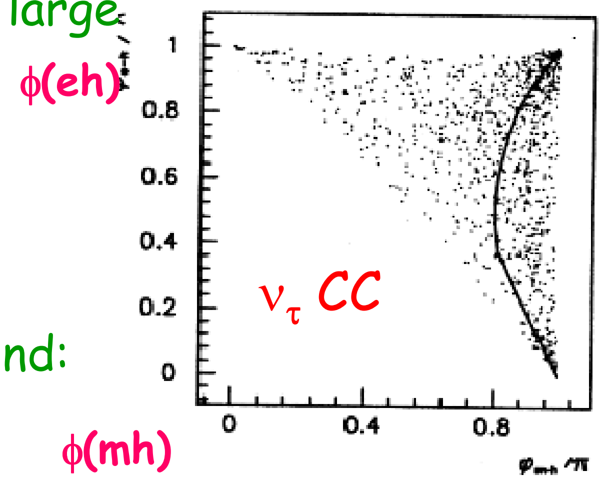
1.3 M νμ CC

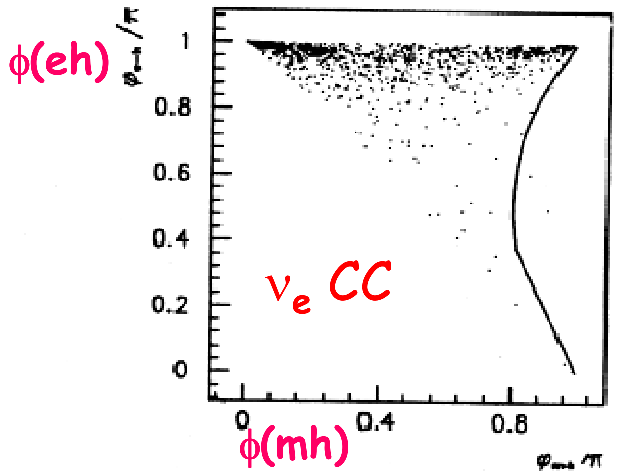
0,4 M νμ NC

13 K νe CC

Exploit the small νe background:

The ϕ- ϕ plot:

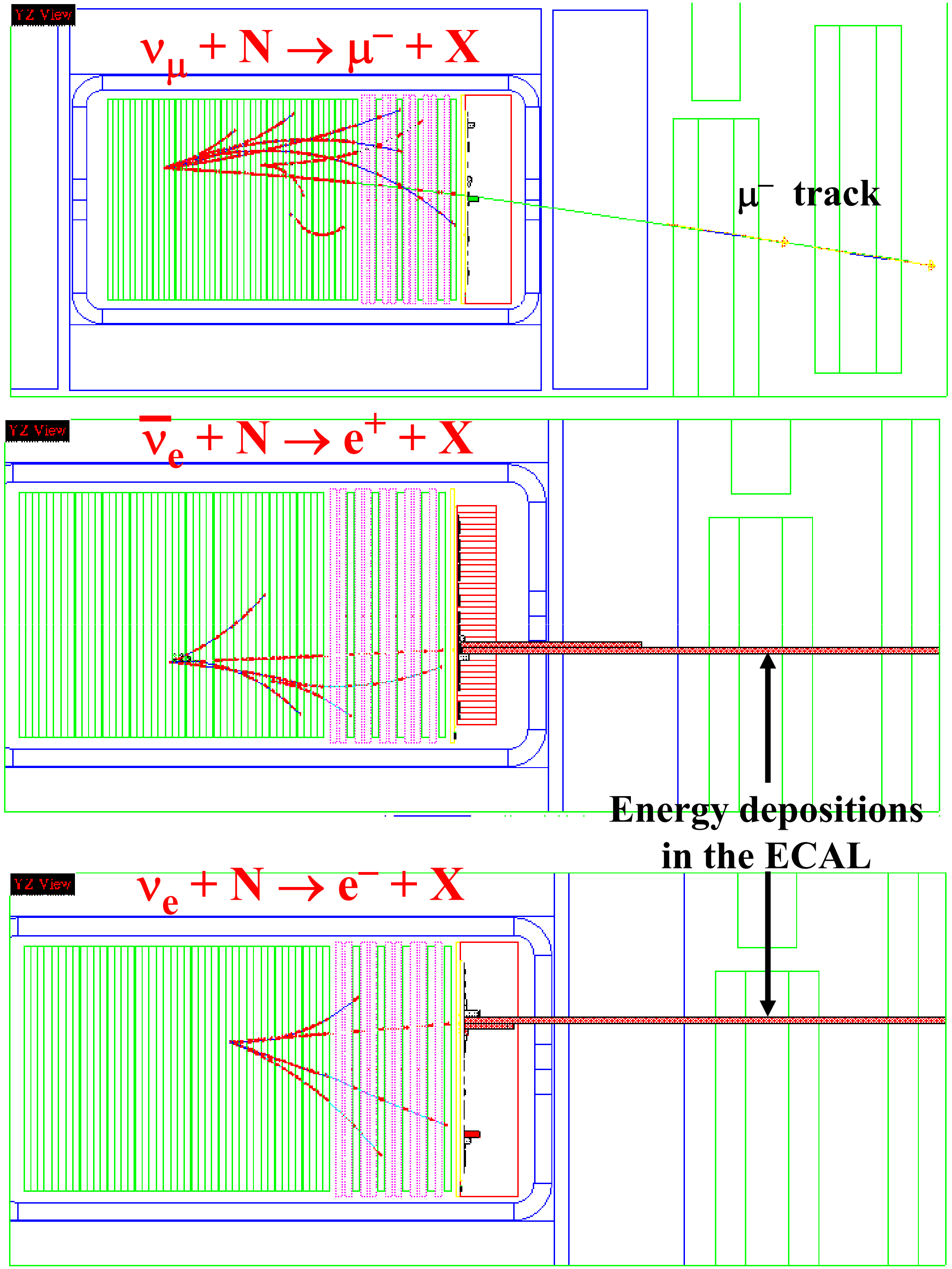


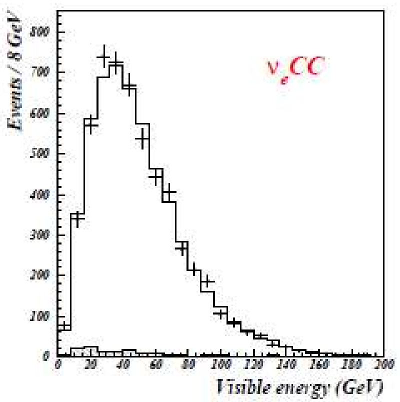


Nomad typical events →

Nomad:

- Modern bubble chamber version
- Very good for electron identification and kinematical measurements
- 3 ton detector, technology not exportable to the kton scale
- Still very good as near detector in a LBL experiment, Nomad-like detector considered for the next LBL experiment in the USA (DUNE)

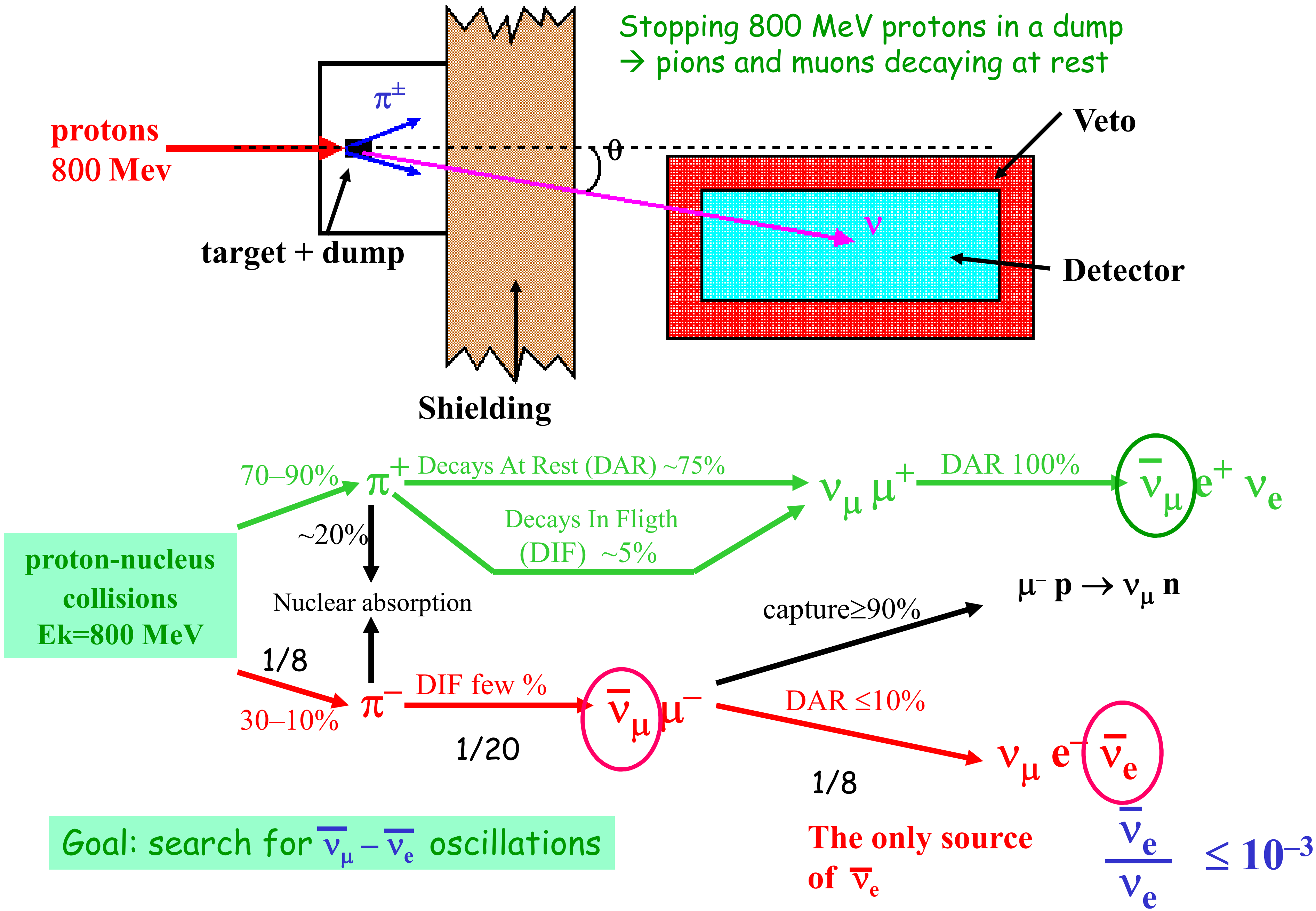




$\nu_\mu \rightarrow \nu_e$ analysis:

5600 ν_e CC events
44% efficiency
98% purity

The LSND experiment (1993-2001)



Goal: search for $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations

LSND result: evidence for $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations (1994)

Signal: Positrons with 20 < *E* < 200 MeV correlated in space and in time with the γ rays of 2.2 MeV expected from the neutron capture:

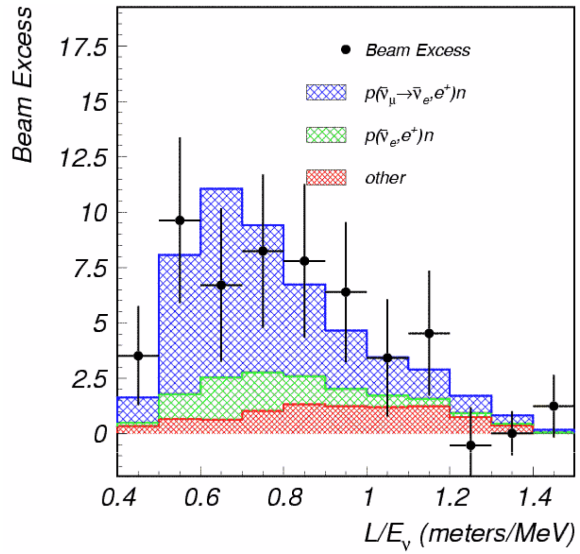
N("beam-on") – N("beam-off") = 117. 9 ± 22.4 events

Background due to μ^- DAR = 19.5 ± 3.9

Background from π^- DIF + ($\bar{\nu}_\mu + p \rightarrow \mu^+ + n$) = 10.5 ± 4.6

Signal $\bar{\nu}_e$ = 87. 9 ± 22.4 ± 6.0 events (stat.) (syst.) 3.8 σ effect

$$\mathcal{P}_{osc}(\bar{\nu}_\mu - \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045) \times 10^{-2}$$

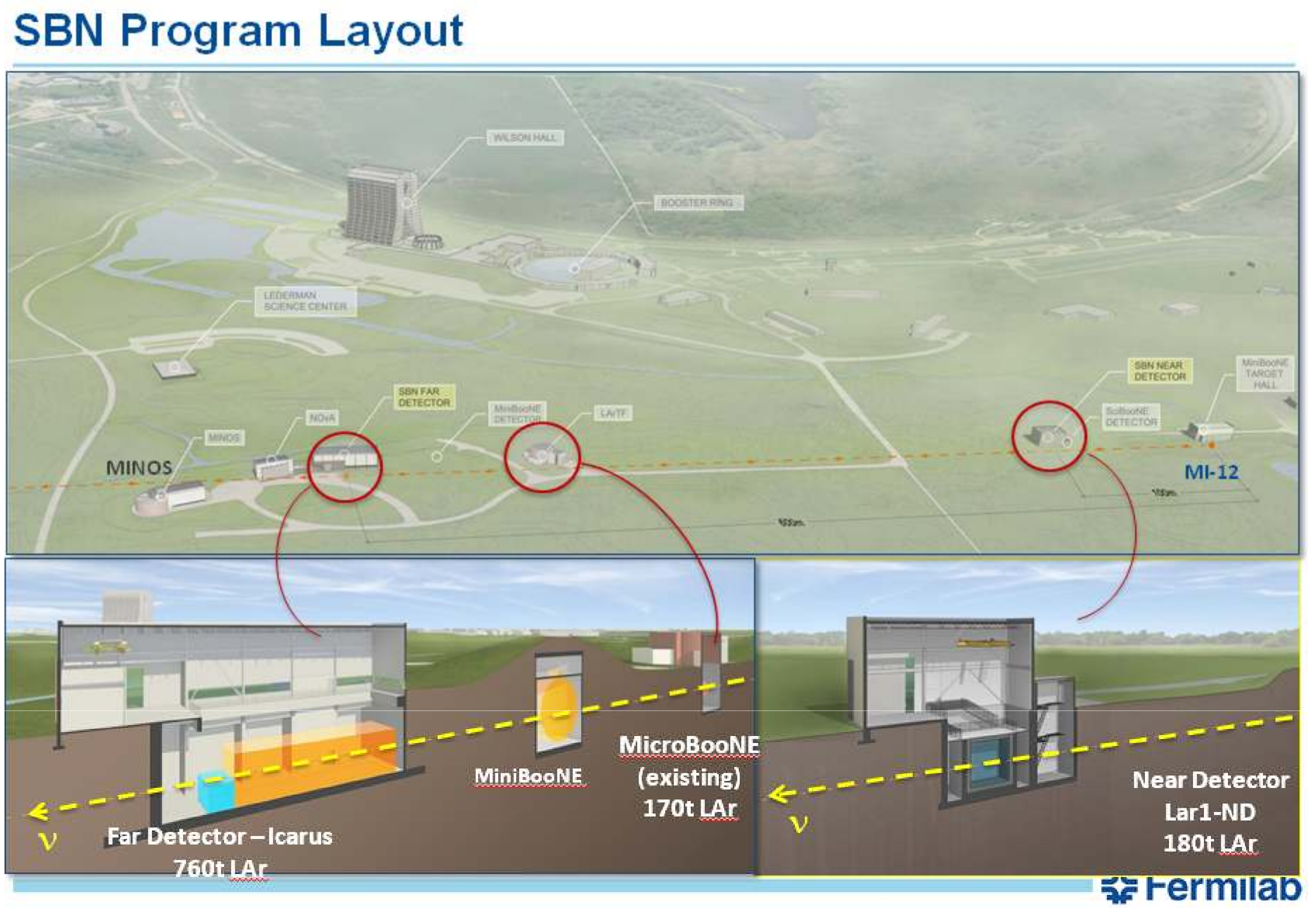


Δm^2 in the eV^2 region

LSND not really confirmed by the dedicated experiment MINIBOONE (2001-2008)

However several ~3 sigma anomalies (LSND, MINIBOONE low energy, Reactor, Cr source) not completely coherent among themselves) are still floating around in the field, feeding theoretical models and additional experimental activity.
These results require more than 3 neutrino flavors to be explained → sterile neutrinos

Very intensive now at FERMILAB with the short-baseline program + experiments at nuclear reactors and with radioactive sources)



Microboone: already built 300 tons Liquid argon detector at the Miniboone position to clarify the MiniBoone low energy anomaly

→ Start data taking this fall

Completion of the program with a near detector SBND and a far detector (ICARUS) put at the optimal length for the oscillations maximum

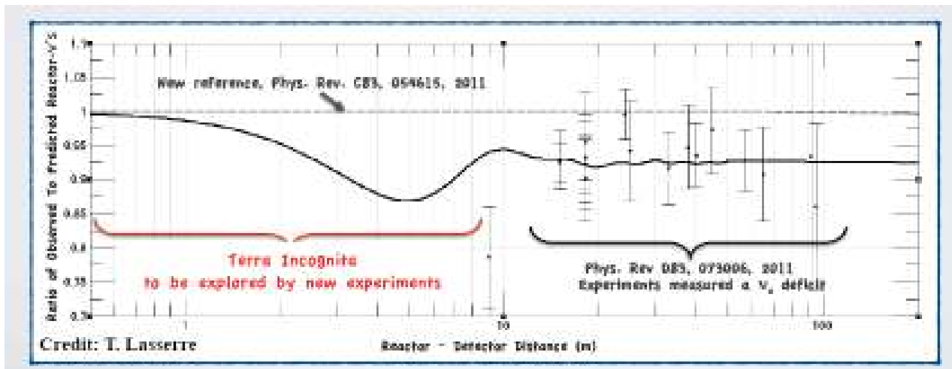
→ Start data-taking in 2018

→ This program should provide a final answer to the LSND anomaly

In parallel searches for sterile neutrinos: large activity of detectors at reactors and combination of existing neutrino detectors with intense radioactive sources trying to clarify the reactor anomaly in terms of neutrino oscillations

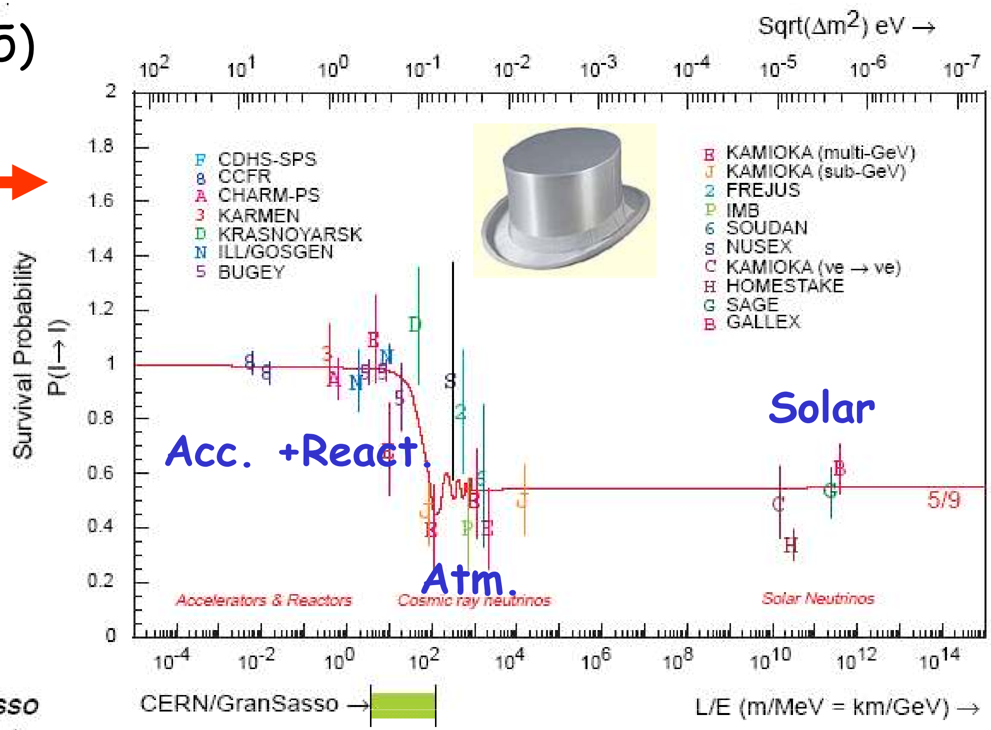
→ detect a disappearance oscillation pattern at short distance, first data in 2016

The reactor neutrinos anomaly, new flux in 2011 6.5% deficit, 3 σ

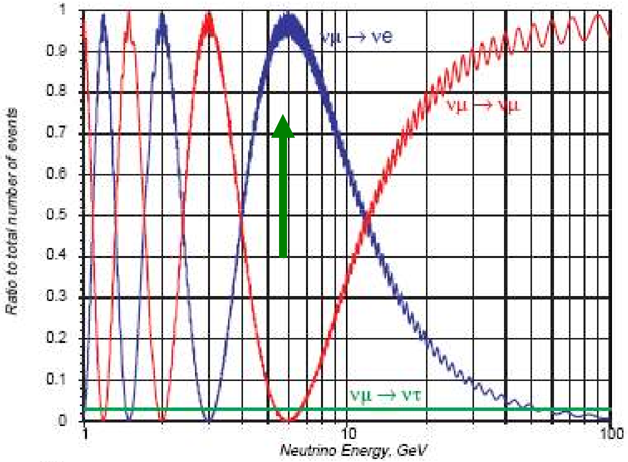


The Perkins plot (PLB 349 1995)

Interpretation of solar + atmospheric data in terms of just one $\nu_\mu \to \nu_e$ oscillation with $\Delta m^2 \sim 10^{-2}$ eV^2



The Acker-Pakvasa 3 flavours model **hep-ph/9611423** included also LSND ($\Delta m^2 \sim 1$ eV^2)

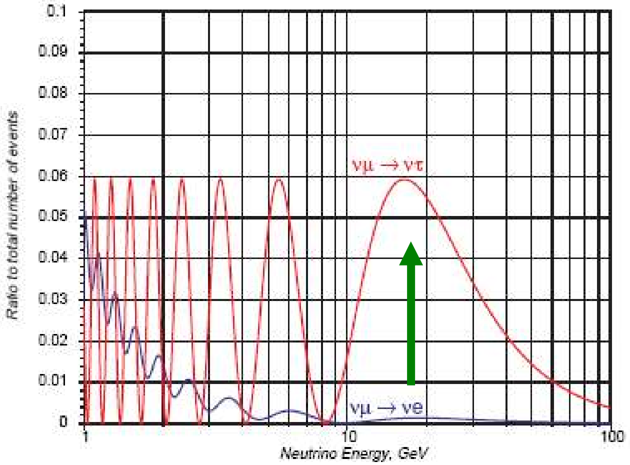


(C) Gran Sasso (735 km)

Icarus SPSLC 96/58 P304 19/12/1996

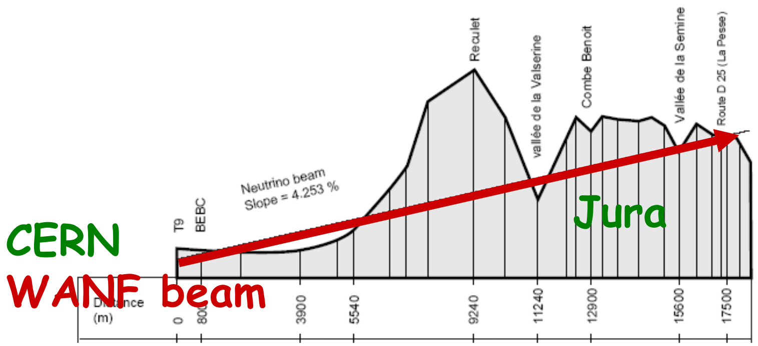
6. **Conclusion**

There is a substantial body of data leading to a theoretical prejudice which suggests that most probably the Gran Sasso and possibly the Jura locations, coupled with the SPS neutrino beam could be the real 'focal point' of the neutrino oscillation search. Spectacular $\nu_\mu \leftrightarrow \nu_\tau$ conversion is expected to be visible behind the Jura and a monumental $\nu_\mu \leftrightarrow \nu_e$ conversion is expected to be observed at the Gran Sasso position.



(B) Behind Jura (17 km)

Medium-baseline L/E~1Km/GeV



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№ 994/31 April 6/10 19 72

Prof. J.N.Bahcall

The Institute for Advanced Study
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Princeton, New Jersey 08540, USA

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I will attend the Balaton meeting on neutrinos and looking forward to see you there.

Yours sincerely,

B.Pontecorvo

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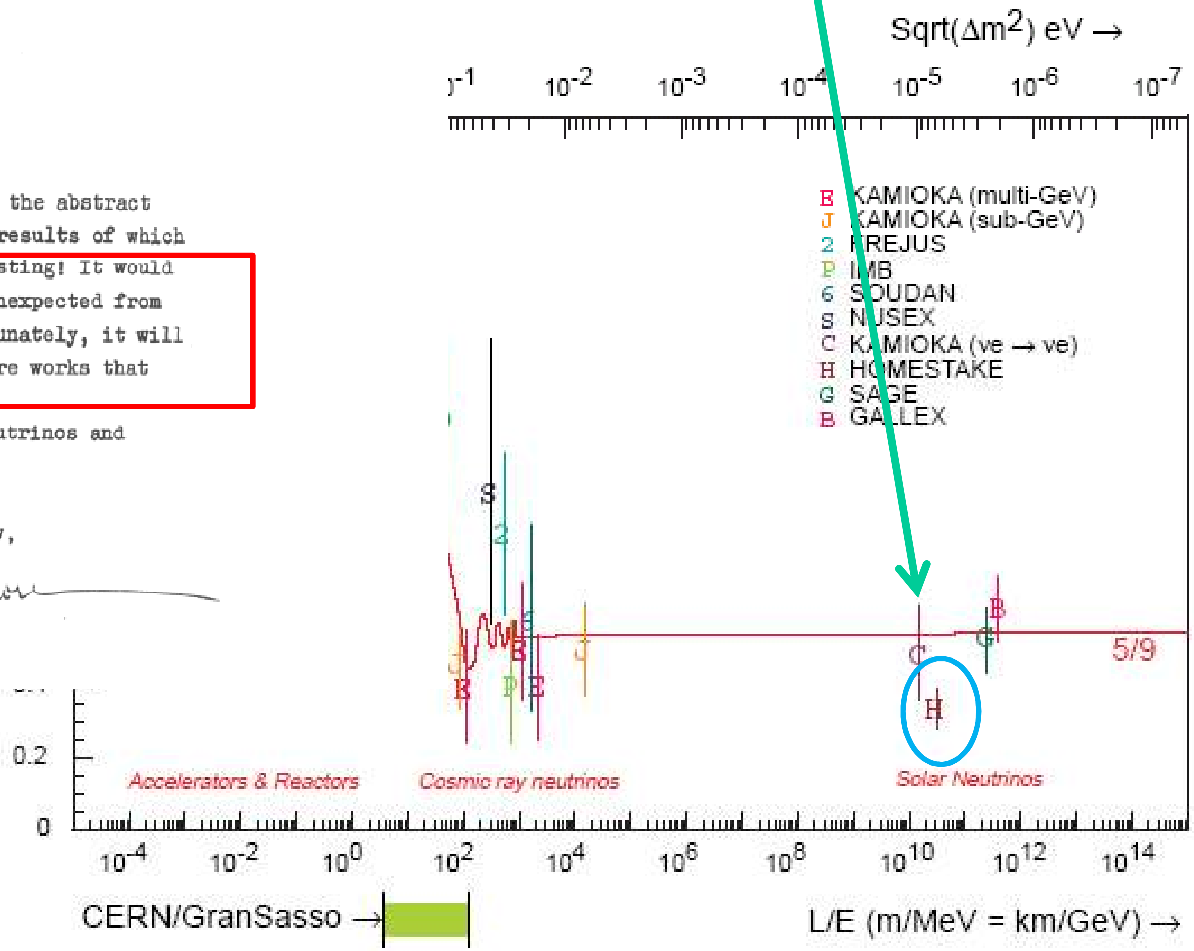
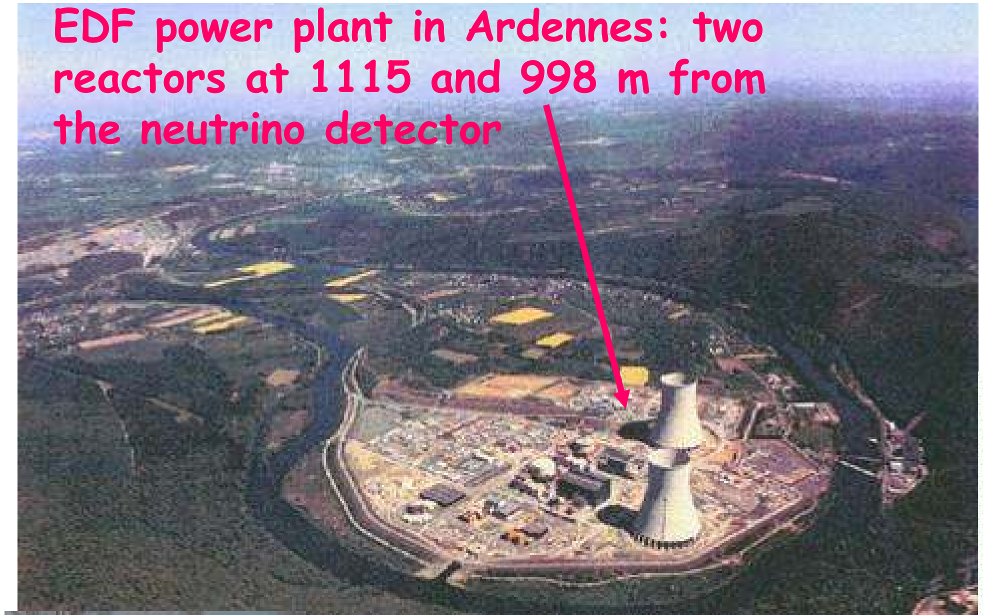
A single outlier point in a plot …
The triumph of Davis, Bahcall, Pontecorvo



CHOOZ (the first long baseline experiment) 1997-1998



EDF power plant in Ardennes: two reactors at 1115 and 998 m from the neutrino detector

$\bar{\nu}_e \rightarrow \bar{\nu}_e$ (disappearance experiment at nuclear reactor)

P_{th}= 8.5 GW_{th}, 1 detector at L ~ 1 km, overburden equivalent to 300 m H_2O, Reactor neutrino flux known at 2.7 %, L/E ~ 330 Km/GeV

Target: 5 ton liquid scintillator target with 0.09% Gadolinium

Prompt annihilation signal (γ rays)

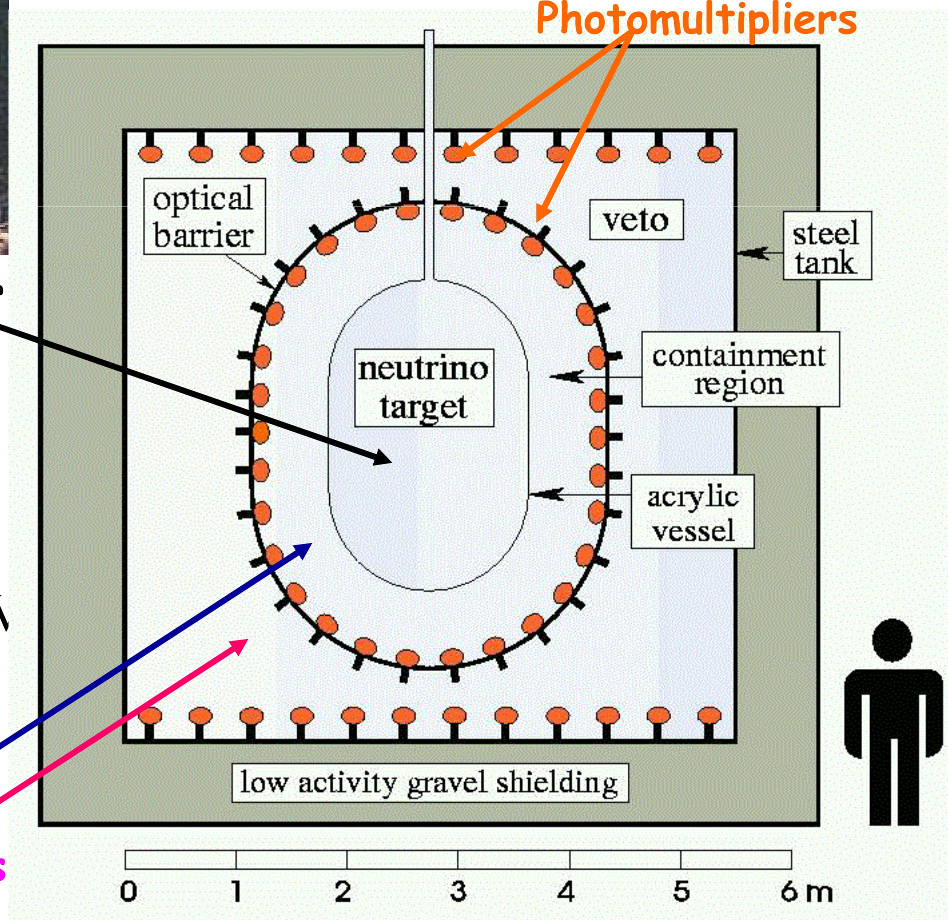
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$n + Gd \rightarrow \gamma \text{ rays } (E_{tot}\ 8.1\ \text{MeV}$$

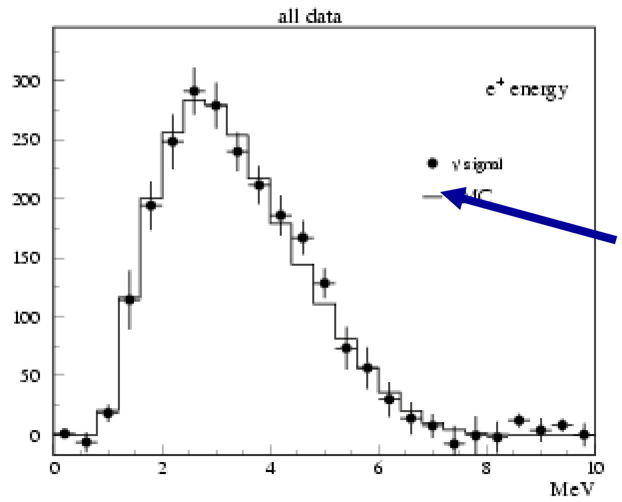
n capture on Gd after thermalization ~30μs

17 ton liquid scint. without Gd (containement of γ rays)

90 ton liquid scint. cosmic rays



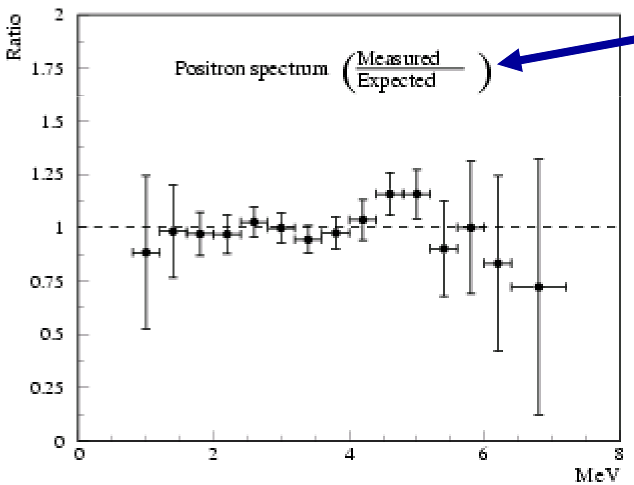
CHOOZ (the first long baseline experiment) 1997-1998



Signal ~ 25 events/day, background (reactors off) ~ 1.2 events/day

Energy spectrum of the positrons compared with the predicted one (no oscillations)

$E(\overline{\nu}_e) = E(e^+) + 1.8$ MeV



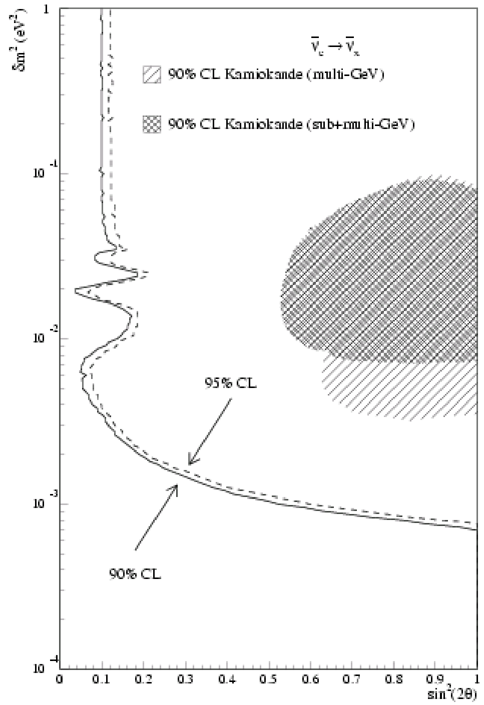
Positron energy (MeV)

Ratio measured/expected

Integrated ratio = $1.01 \pm 0.028 \pm 0.027$

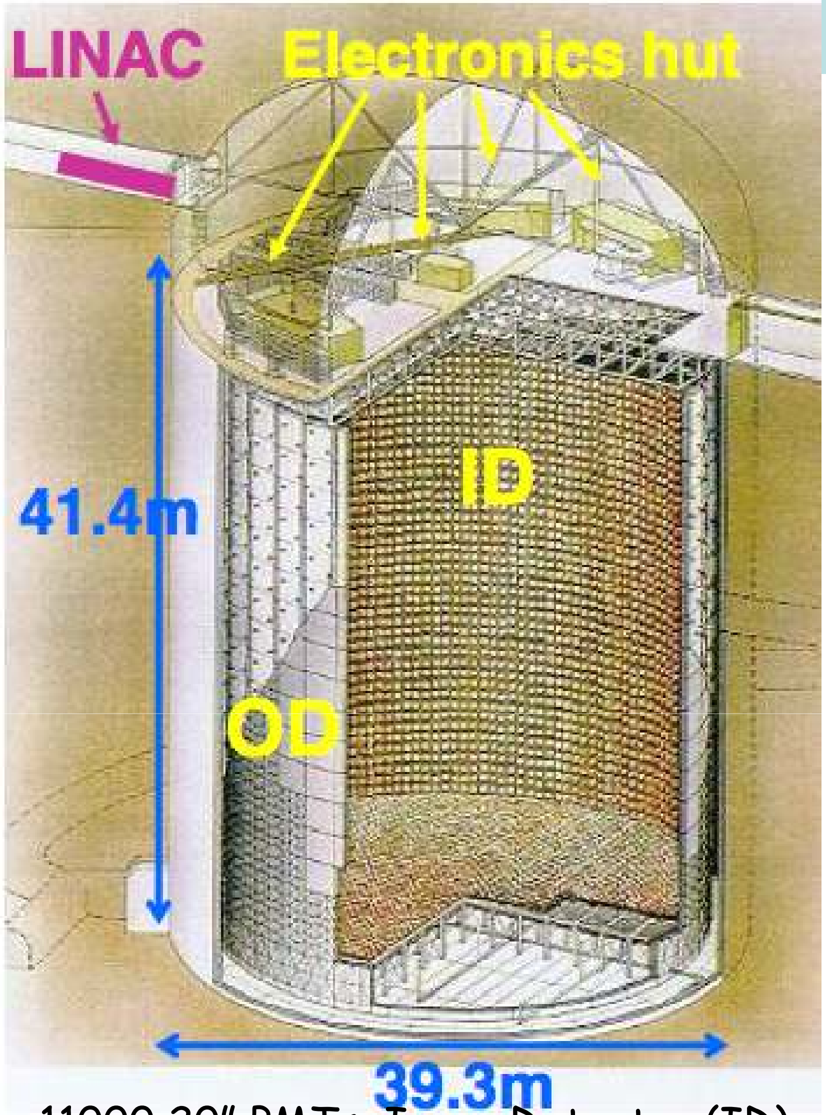
CHOOZ did not observe a significative deficit of ν_e

NO « monumental » $\overline{\nu}_e \rightarrow \overline{\nu}_\mu$ conversion



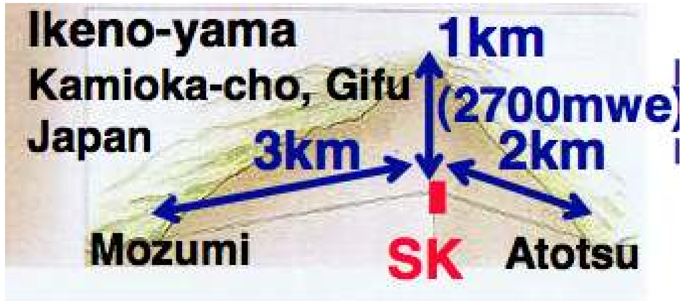
This result was published in 1998 <u>before</u> the Super-Kamiokande results and excluded the atmospheric neutrino anomaly interpretation in terms of $\nu_\mu \rightarrow \nu_e$ oscillations

The Super-Kamiokande detector



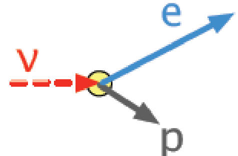
~11000 20” PMTs Inner Detector (ID) (40% coverage)

Proton decay, solar neutrinos, atmospheric neutrinos, supernovae neutrinos + accelerator neutrinos (K2K, T2K)



- 50 Kton Water Cherenkov detector (fiducial volume 22.5 Kton)
- Operation since April 1996 (accident in 2001 recovered in 2006)
- Dead-time less DAQ system (2008~)

- Detector performance well-matched to sub-GeV neutrinos:
  - Excellent performance for single particle events
  - Good e-like(shower ring) / μ-like separation
  - Quasi-elastic scattering dominant in sub-GeV region.
  - νe signal: $\nu_e + n \rightarrow e + p$



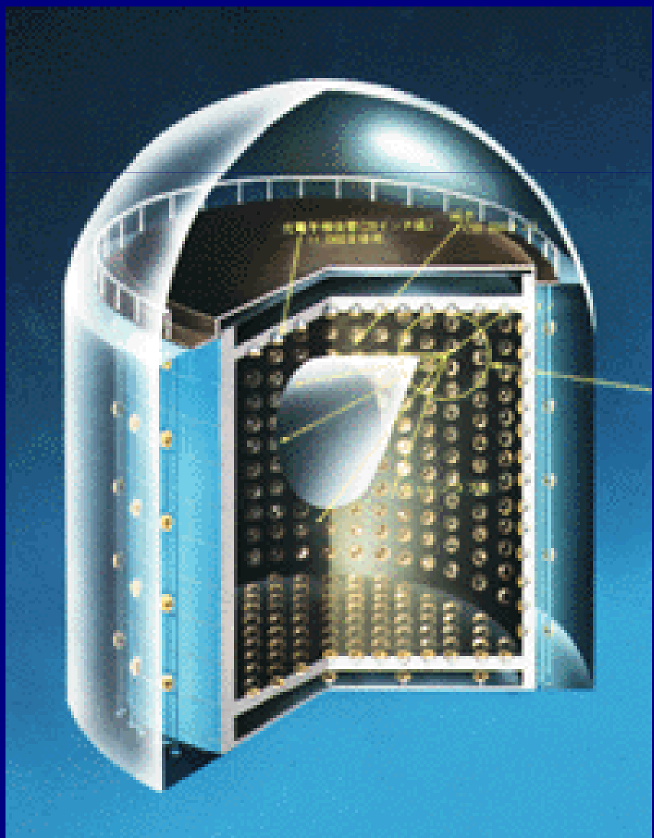
proton not detected (below Cerenkov threshold)

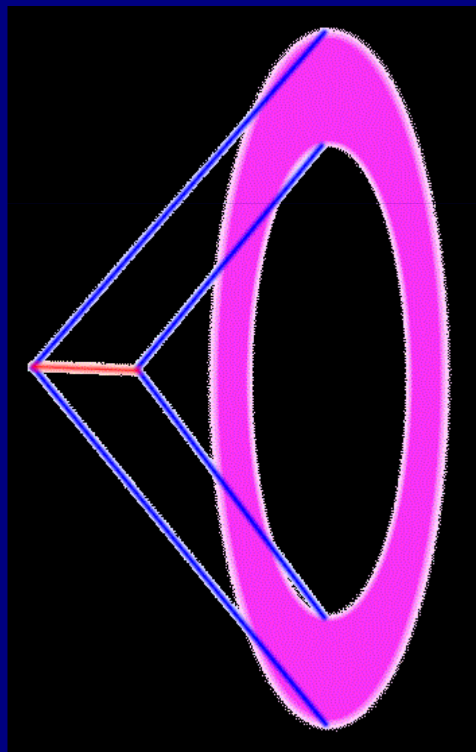
particle	p (threshold)
e	660keV
μ	137MeV
$\pi^{\pm}$	175MeV
K	650MeV
p	1300MeV

Cerenkov radiation emitted if v>c/n
→ threshold velocity $\beta_t = 1/n$

- For water n(280-580nm)~1.33
- Threshold Angle: 42°

$$\cos\theta_C = \frac{1}{n\beta} \quad \text{with} \quad n = n(\lambda) \geq 1$$





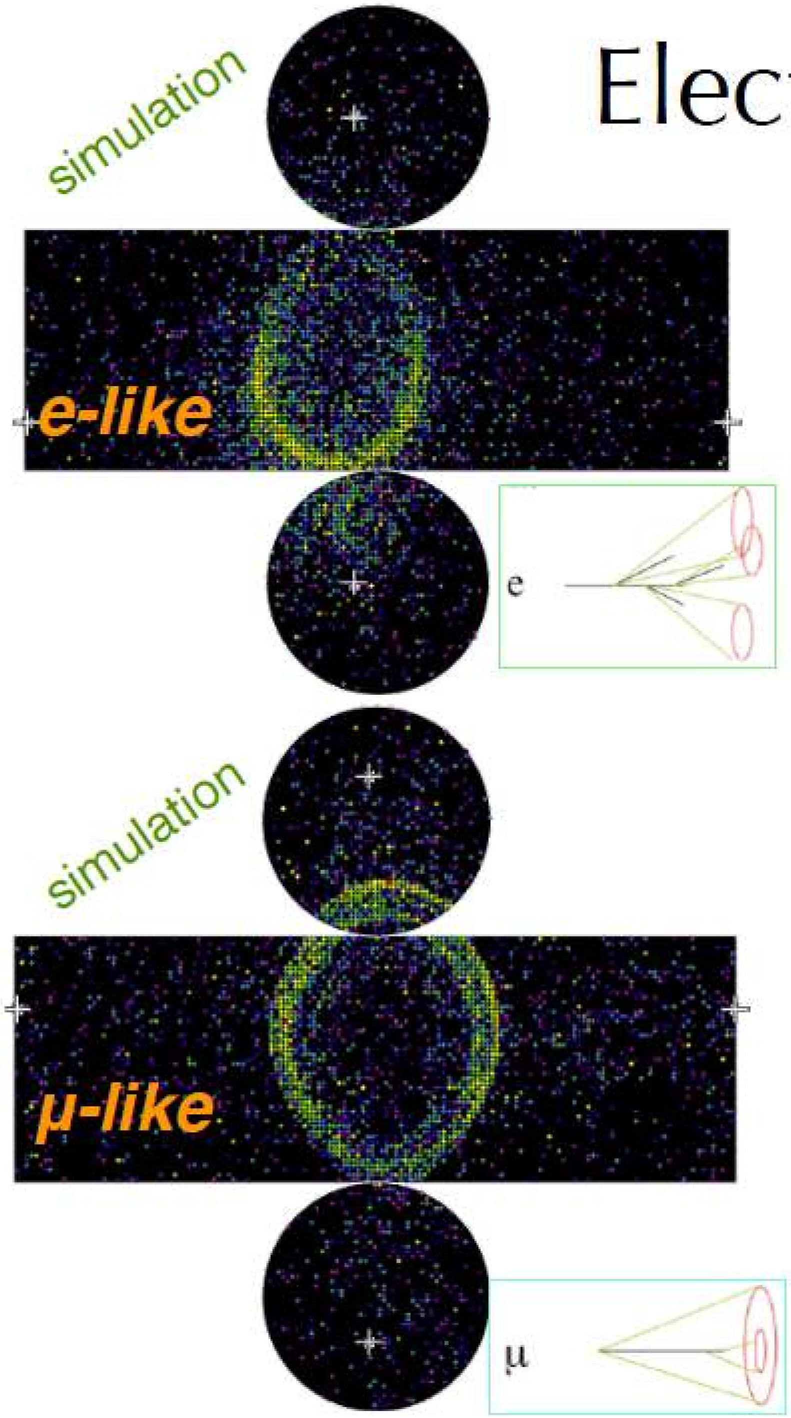
Muons:
Clean rings

Electrons:
Showers → fuzzy rings

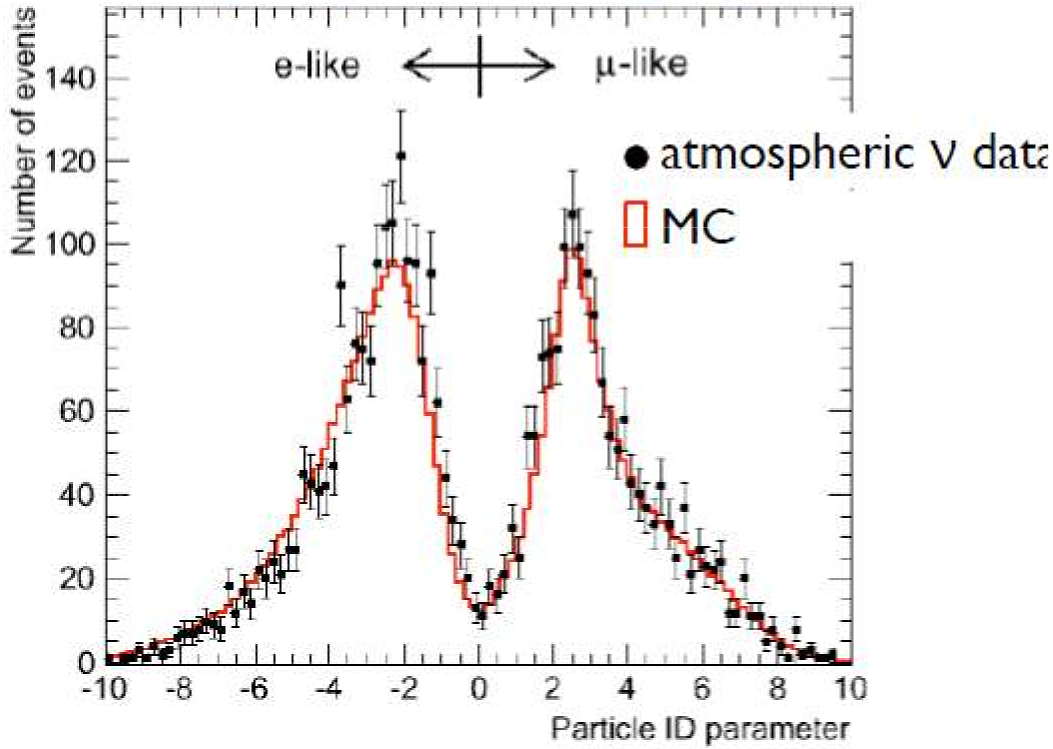
→ Electron muon separation at ~1% level with the ring shape

- Direction from the ring,
- Interaction vertex position from arrival time of light on the photomultipliers
- Energy measurement for contained events

Electron-like and muon-like event at SK



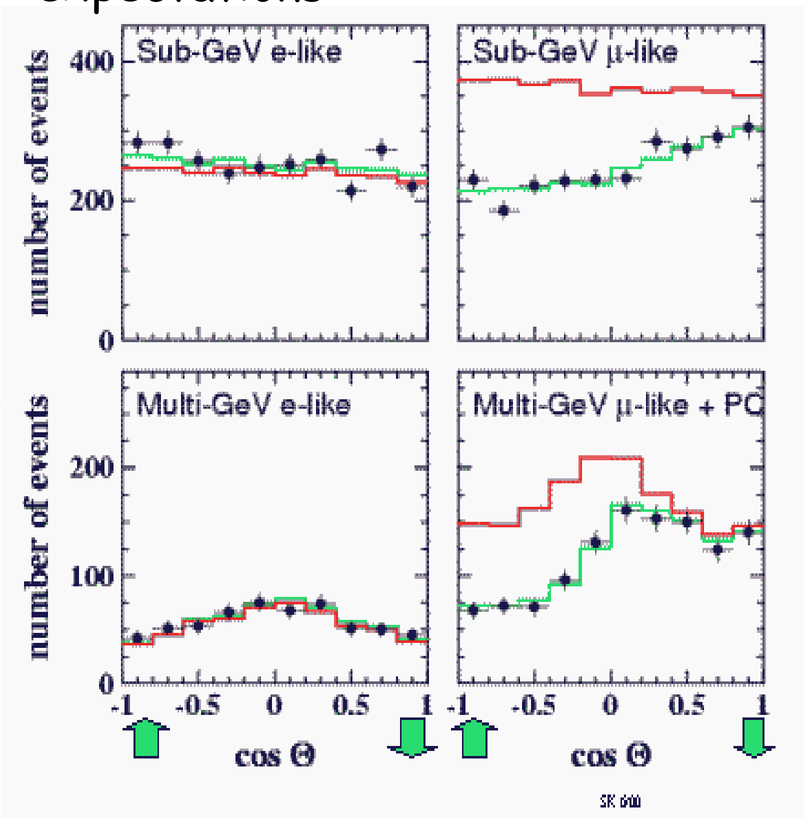
Particle identification using ring shape & opening angle



Probability that μ is mis-identified as electron is ~1%

Neutrino 98 Conference in Takayama (June 1998)

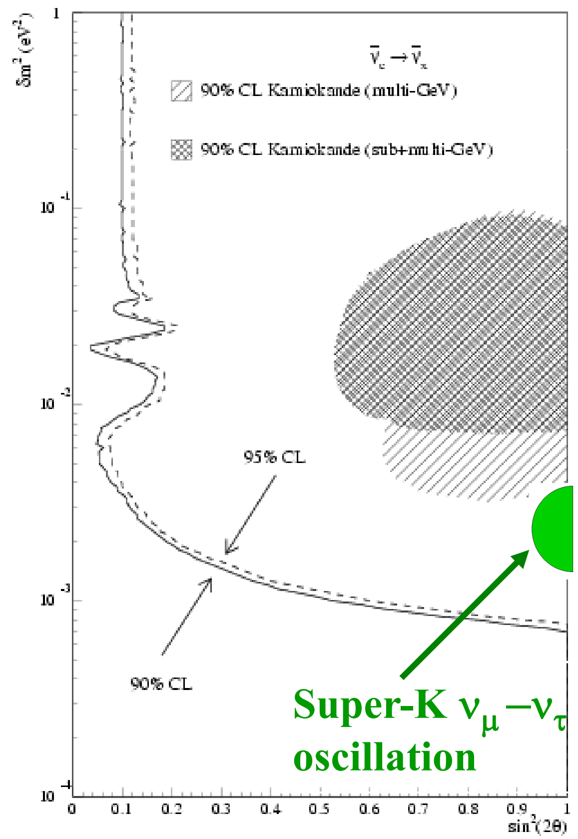
First results from Super-Kamiokande on atmospheric neutrinos, evidence of a zenith angle dependence of ν_μ disappearance, ν_e in agreement with expectations



SK: Atmospheric neutrinos anomaly

intepretable in terms of $\nu_\mu \rightarrow \nu_\tau$ oscillations with a Δm^2 ~ a few 10^{-3} eV^2

CHOOZ: no $\nu_\mu \rightarrow \nu_e$ oscillations, Θ_{13}<11°



Neutrino oscillations start to be taken seriously as explanation of the atmospheric neutrinos anomaly

Opens a campaign for a new generation of long baseline experiments to provide a final proof

CERN 4/7/2000

HIGHLIGHTS OF THE

NEUTRINO 2000 CONFERENCE

SUDBURY JUNE 16-21 2000

D. AUTIERO

CERN/EP

SNO and Kamland at the close horizon
LBL experiments K2K, MINOS launched

CONCLUSIONS

ARE WE GOING TO SEE IN THE NEXT 10 YEARS A CLARIFICATION OF NEUTRINO OSCILLATIONS SCENARIOS?

- SOLAR NEUTRINOS: ✓

  $3 \div 5$ YEARS SNO, SUPERK, KAMLAND, BOREXINO + ...

- LONG BASELINE: ✓

  IF $\Delta m^2 \sim 3 \cdot 10^{-3}$
  - 4 YEARS K2K @ 4σ
  - FROM 2005 CNGS τ APPEARANCE
  - FROM END 2003 MINOS: OSCILLATION PATTERN MEASUREMENT OF THE PARAMETERS
  - IN THE MEAN TIME SUPERK CONTINUES WITH ATMOSPHERIC ν_s

- LSND
  - MINIBOONE 3 YEARS **Wrong !**

- MEASUREMENTS OF m_ν
  - $0\nu\beta\beta$ (FUTURE SENSITIVITIES $\sim 10^{-2}$ eV)
  - COSMOLOGY CBR MAP, PLANCK ✓

    BIG REVOLUTION, ALREADY FROM BOOMERANG AND MAXIMA + LARGE SCALE STRUCTURES ⇒ INDEPENDENT CONFIRMATION OF Ω_Λ

    Even better! PLANCK MAY DETERMINE $\Sigma m_\nu \sim 0.4$ eV

A simple but extremely successful research line …
→ the very good historical record of the detectors at Kamioka:

- ✓Kamiokande 1987: Observation of SN1987a
- ✓Kamiokande: Solar neutrino deficit (B neutrinos) and first measurements of atmospheric neutrinos
- ✓Super-K 1998: Solid evidence for atmospheric neutrinos deficit (zenith angle)
- ✓Super-K 2000: Measurements on solar neutrinos favoring LMA solution
- ✓Kamland (recycling of Kamiokande with liquid scint.) 2002 solar neutrino oscillations with far reactors
- ✓Super-K (K2K) 2004 first long-baseline accelerator experiment, evidence for $\nu\mu$ disappearance
- ✓Super-K (T2K) 2011 first indication of ν_e appearance, θ_{13} just below CHOOZ limit, the most favorable situation

D.A. CERN seminar on 4/7/2000: "Highlights of the Neutrino 2000 conference"

Wondering about future results from K2K and Kamland:
"are the Japanese people going to continue with an unprecedented sequence of results"

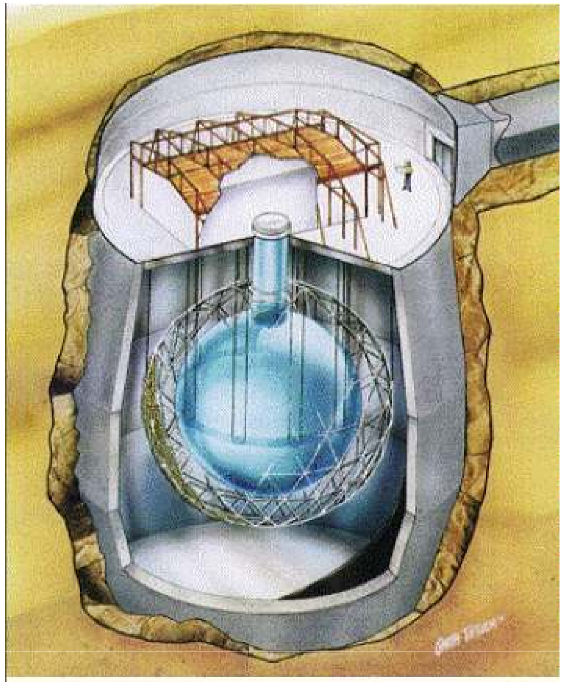
Answer in 2015: definitively yes, even more than expected !

Another (big) advantage: the analysis of Super-K, software and event selection criteria are stable and very well understood since > 13 years

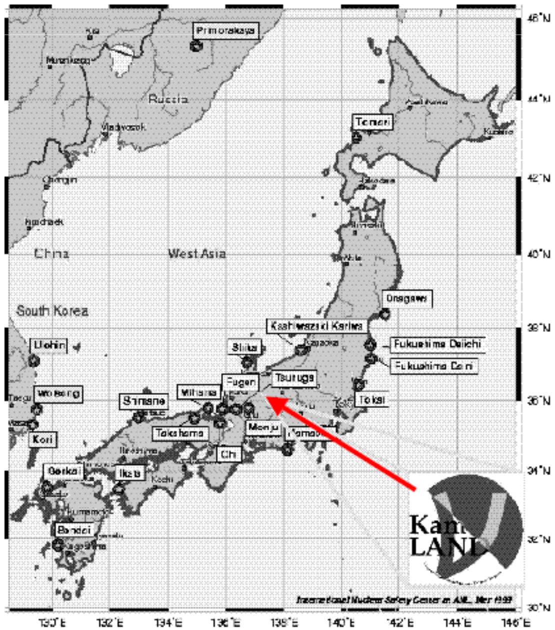
The final proof for solar neutrinos:

2001: SNO 1000 tons of heavy water, sensitive to neutral current reactions → measure the total neutrino flux independently from their flavor

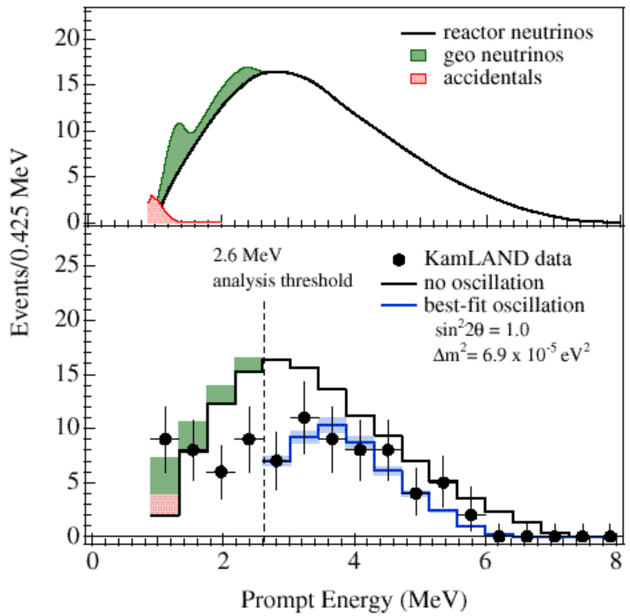
(NC) $\nu + d \rightarrow \nu + p + n$



The total neutrino flux agrees with the SSM !
Electron neutrinos change into other neutrinos

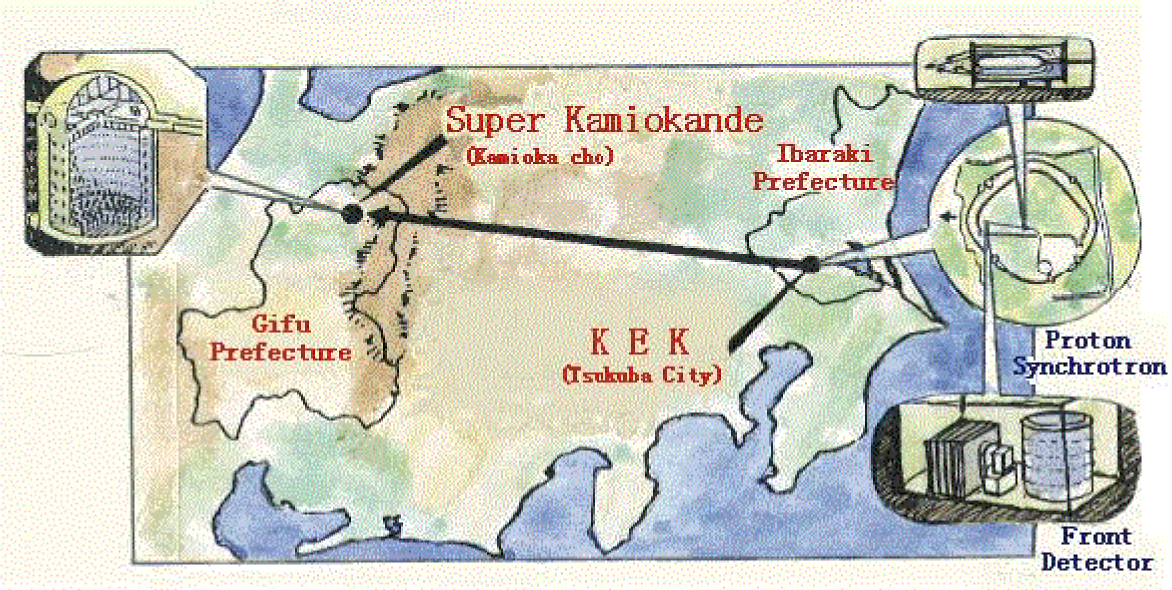


2002: Kamland reactor experiment 1000 ton liquid scintillator reproduces the solar neutrino oscillations on earth using antineutrinos from far reactors (on average 180 km)



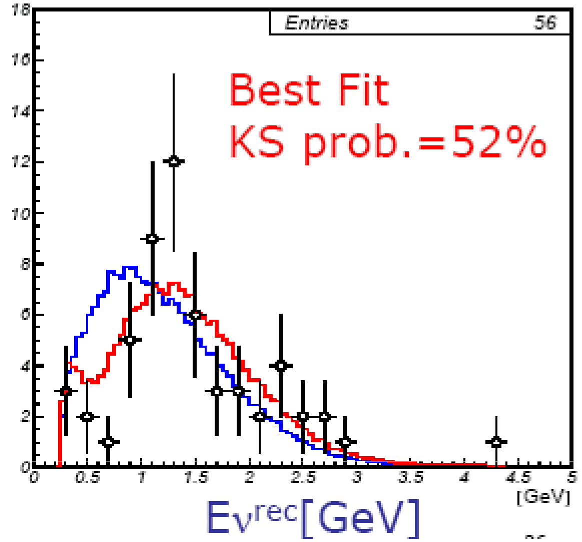
Typical Theorists' View 1990

- Solar neutrino solution *must* be small angle MSW solution because it's cute   Most likely wrong!
- Natural scale for $\Delta m^2_{23} \sim 10–100\ \mathrm{eV}^2$ because it is cosmologically interesting *Wrong!*
- Angle θ_{23} must be of the order of V_{cb} *Wrong!*
- Atmospheric neutrino anomaly must go away because it needs a large angle   *Wrong!*

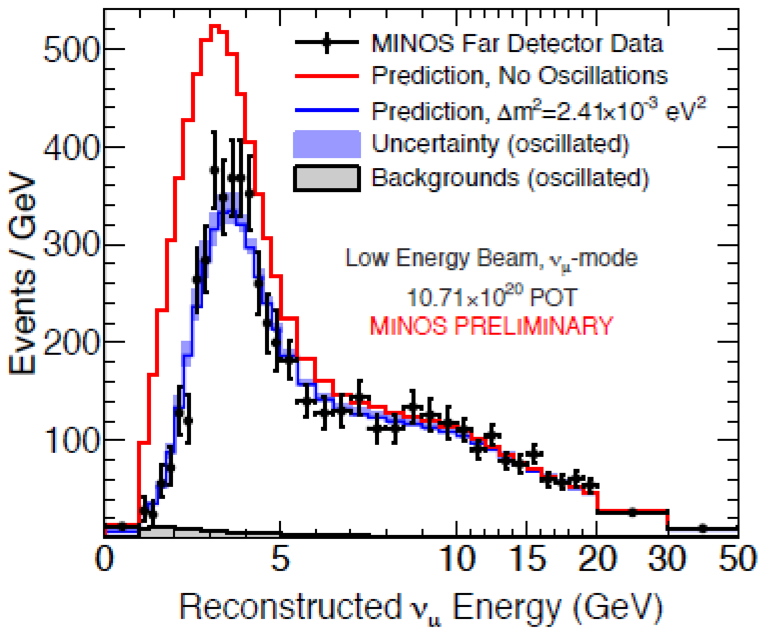


K2K results in 2004

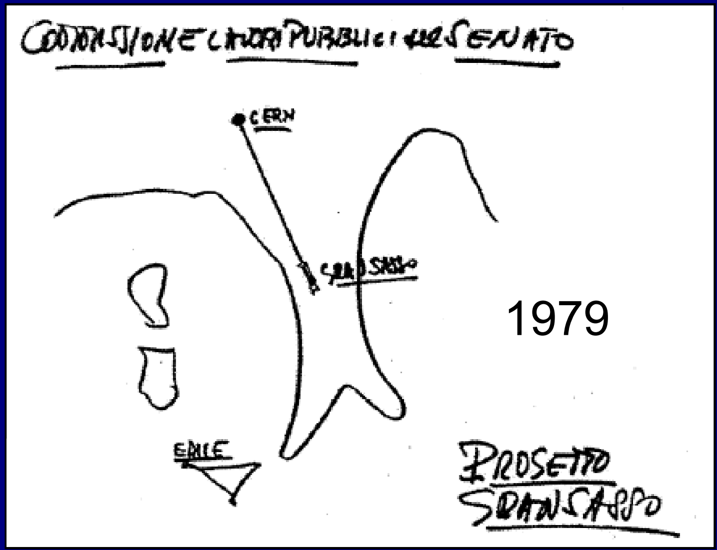
- $N_{SK}^{obs}=108$
- N_{SK}^{exp} (best fit)$=104.8$



MINOS (U.S.) results in 2006



→ Confirmation of SuperKamiokande atmospheric neutrino results with accelerator neutrinos



Cern Neutrinos to Gran Sasso

- Unambiguous evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the region of atmospheric neutrinos by looking for ν_τ appearance in a pure ν_μ beam
- Search for subleading $\nu_\mu \rightarrow \nu_e$ oscillations

- Beam: CNGS (1999)
- ν_τ appearance experiments at LNGS
- No near detectors needed in appearance mode

CNGS1 (2000) OPERA

CNGS2 (2002) ICARUS

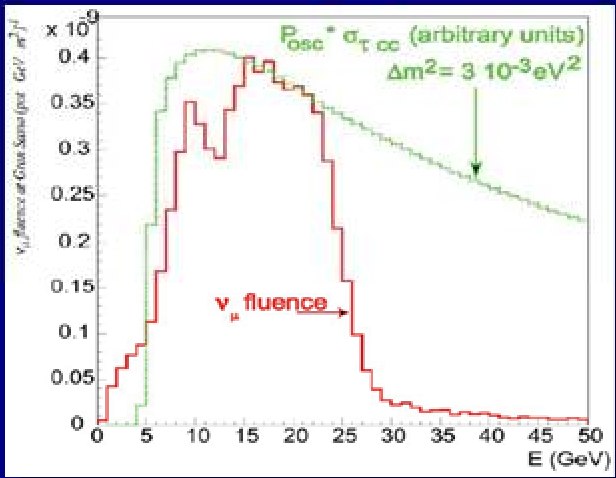
$$N_\tau \approx 1.61 \sin^2(2\theta)(\Delta m^2)^2 L^2 \int_{3.5\,GeV}^{E_{max}} \Phi_\mu(E) \frac{\sigma_\tau(E)}{E^2} dE$$

Quantity to be optimized playing with the beam spectrum:
ν_μ flux vs $\sigma(\tau)/E^2$

→ produce the max. number of $\nu\tau$ CC

Dependence of the events rate on $(\Delta m^2)^2$

Signal constant as a function of L for L << λ
Φ_μ contains a factor $1/L^2$



CNGS fluxes

<E (ν_μ)>	17 GeV
L	730 km
L/E	43 Km/GeV
$(\nu_e + \nu_e)/\nu_\mu$ cc	0.87%
ν_μ / ν_μ cc	2.1%
ν_τ prompt	negligible

- **Nominal beam performance ($4.5\ 10^{19}$ pot/y)**
- **OPERA Target mass of 1.25 kton**

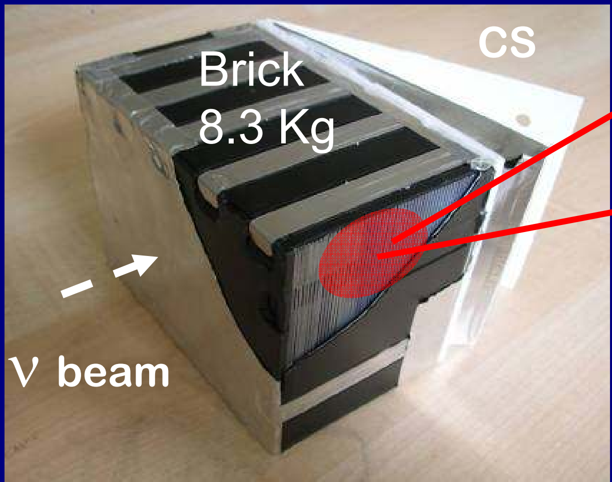
→ Expected number of interactions in 5 years :
~ 23600 ν_μ CC+NC
~ 170 ν_e + ν_e CC
~ 115 ν_τ CC ($\Delta m^2 = 2.5 \times 10^{3}\ eV^2$)

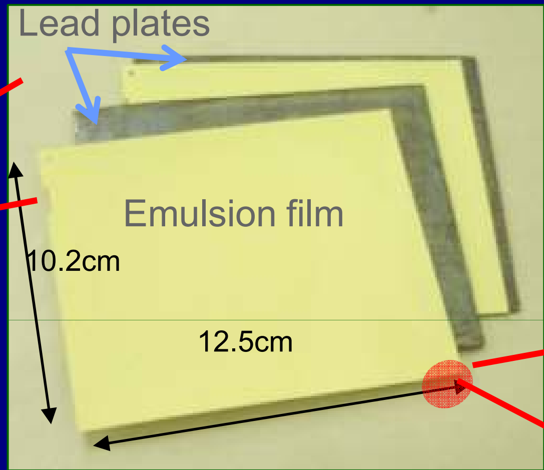
After efficiencies, 8 tau decays are expected, with <1 background events

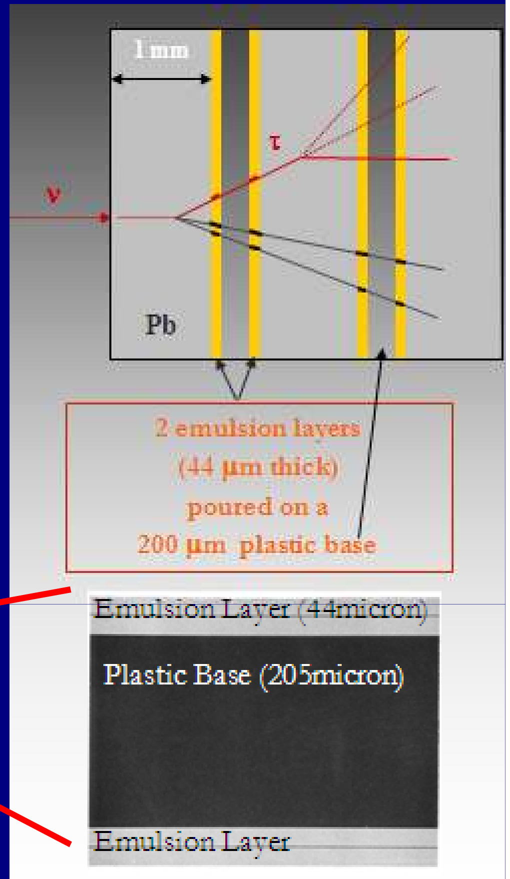
OPERA basic unit: the « Brick »

Based on the concept of the **E**mulsion **C**loud **C**hamber :
- 57 emulsion films + 56 Pb plates
- interface to electronic detectors: removable box with 2 films (Changeable Sheets)

→ High space resolution in a large mass detectors with a completely modular scheme





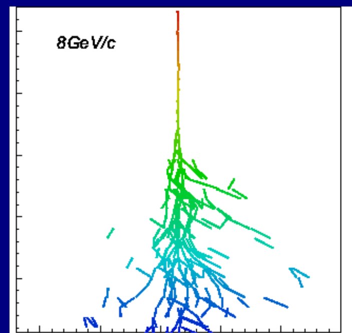


Tracks reconstruction accuracy in emulsions:

$\Delta x \approx 0.3\ \mu m$ $\Delta\theta \approx$ **2 mrad**

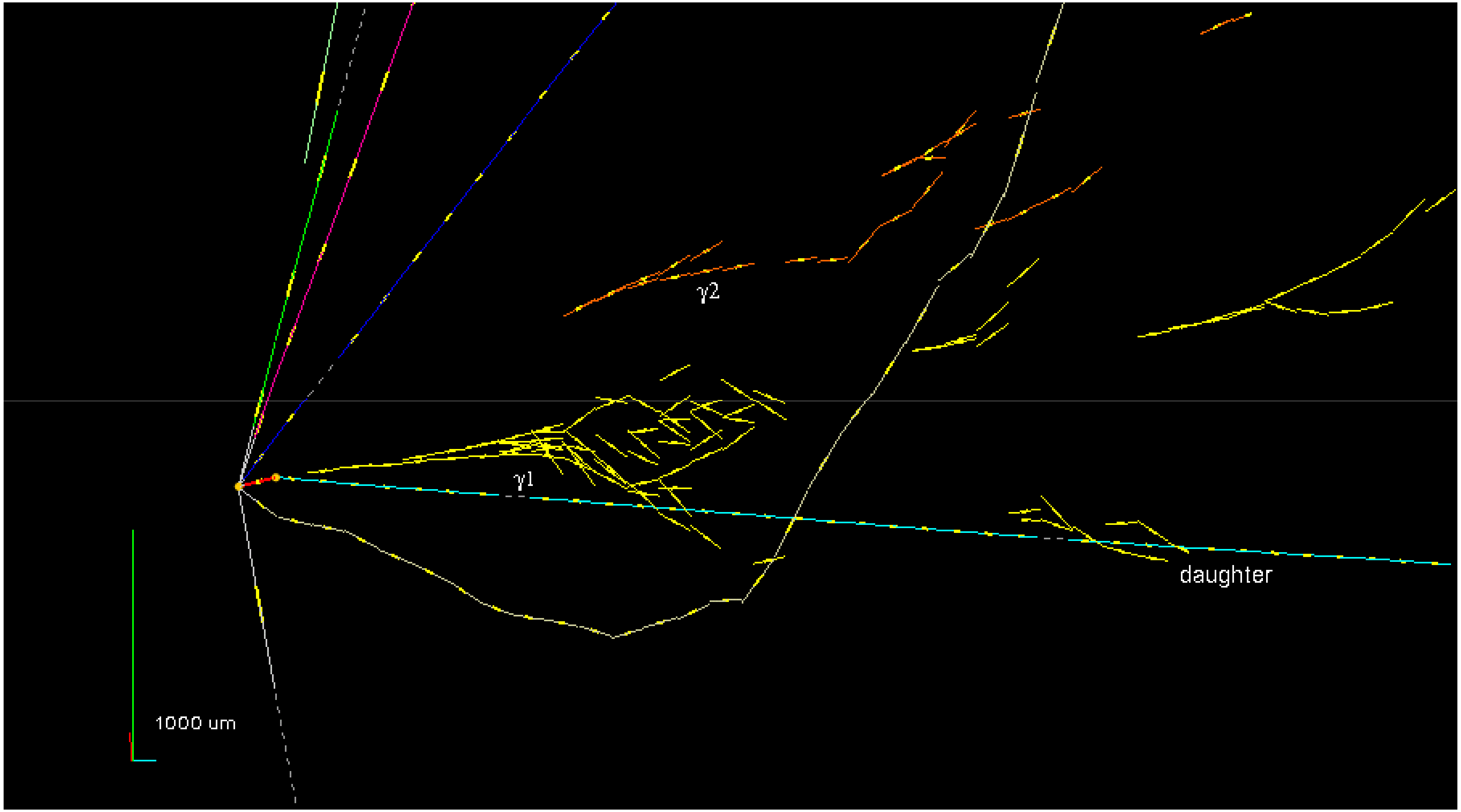
Bricks are complete stand-alone detectors:

- ✓ Neutrino interaction vertex and kink topology reconstruction
- ✓ Measurement of hadrons <u>momenta</u> by multiple Coulomb scattering
- ✓ <u>dE/dx:</u> pion/muon separation at low energy (at end of range)
- ✓ Electron identification and measurement of the energy of electrons and gammas (<u>electromagnetic calorimetry</u>)



First OPERA ν_τ candidate
(single hadronic prong τ decay)

http://arxiv.org/abs/1006.1623
Physics Letters B (PLB-D-10-00744)



$$\nu_\tau + N \rightarrow \tau^- + X$$
$$\tau^- \rightarrow \rho^- + \nu_\tau$$
$$\rho^- \rightarrow \pi^- + \pi^0$$
$$\pi^0 \rightarrow \gamma + \gamma$$

Visible tau decay topology
with kink and two gammas

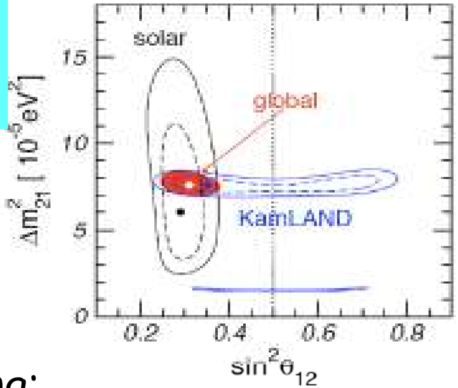
Standard 3 ν framework (ignoring LSND, Miniboone anomaly, Reactors anomaly, Cr source anomaly …)

Two almost independent oscillations describing;

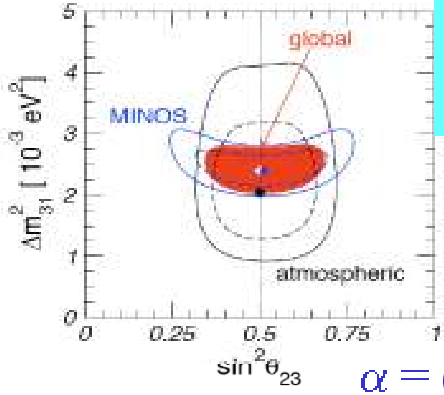
solar neutrinos: Δm^2_{21} $(7.65^{+0.23}_{-0.20})\,10^{-5}\,\mathrm{eV}^2$; $\sin^2\theta_{12}$ $0.304^{+0.022}_{-0.016}$ and atmospheric neutrinos: $|\Delta m^2_{31}|$ $(2.40^{+0.12}_{-0.11})\,10^{-3}\,\mathrm{eV}^2$; $\sin^2\theta_{23}$ $0.50^{+0.07}_{-0.06}$

Solar neutrinos
+ Kamland
ν_e, anti-ν_e disappearance

L/E~15 Km/MeV



L/E~500 Km/GeV



Atmospheric neutrinos
+ accelerators
ν_μ disappearance

3 neutrino flavours mixing:
favorite parametrization of U:
in terms of 3 mixing angles θ_{12} θ_{23} θ_{13} and one Dirac-like CP phase δ :

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

$\alpha = e, \mu, \tau$ (flavor index)
$i = 1, 2, 3$ (mass index)
$U_{\alpha i}$= unitary mixing matrix

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

Atmospheric ν oscillations   Solar ν oscillations

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

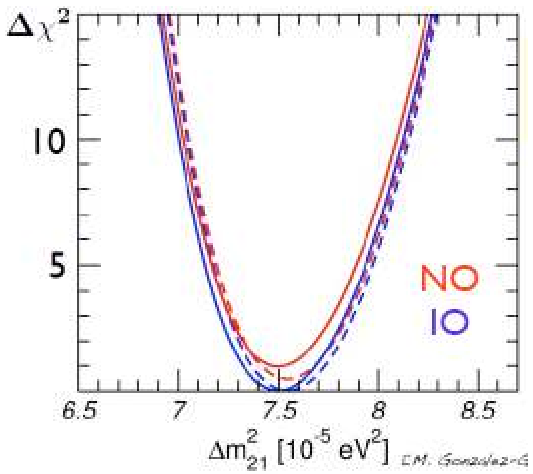
where: $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$.

Bridge

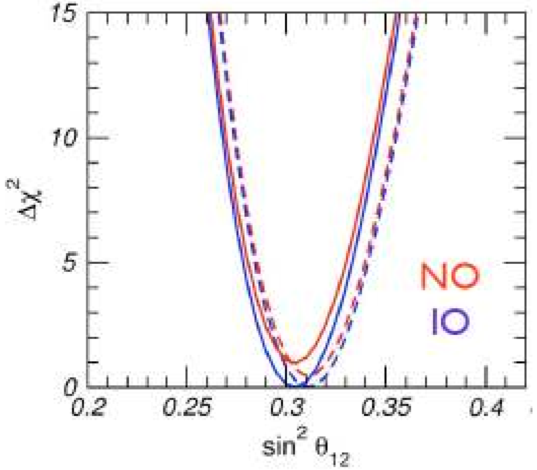
θ_{13},CP violation?

Most of the 3 angles and 2 Δm^2 parameters are known by global fits with <5% accuracy

NUFIT 2014

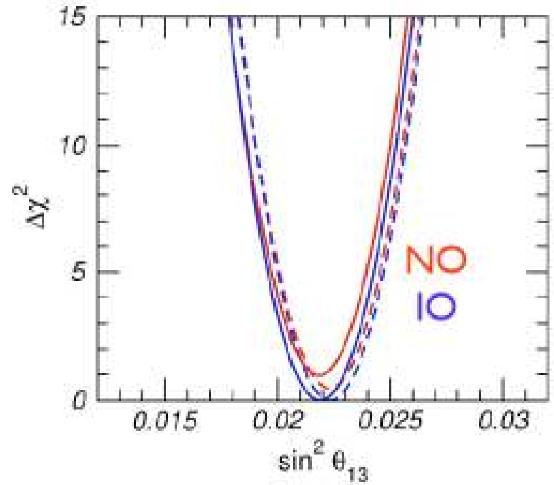


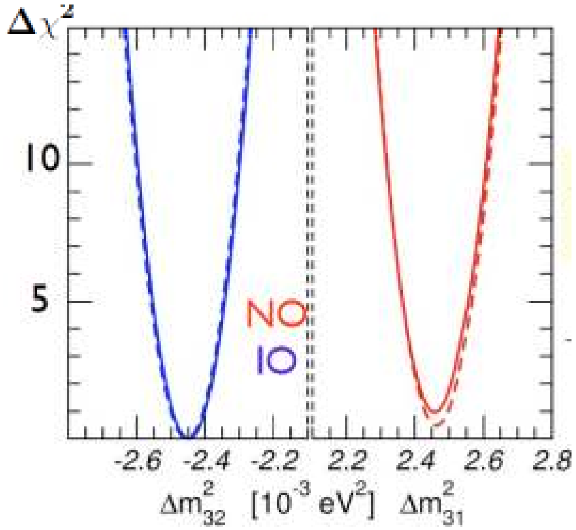
Δm^2_{21} = 7.5 +_0.19 eV^2 2.4%



$\sin^2\theta_{21}$ = 0.304 +_0.013 4.3%

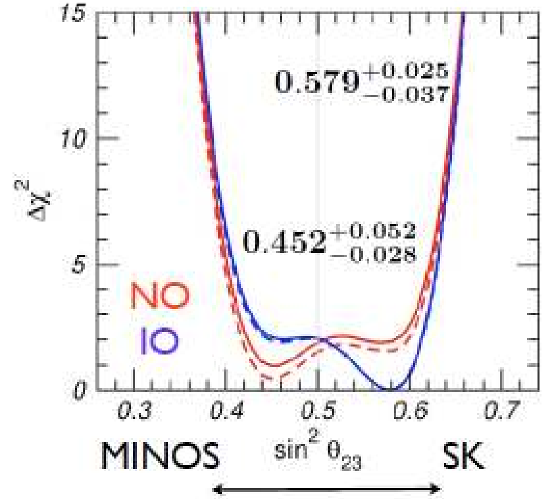
$\sin^2\theta_{13}$ = 0.0218 +_0.0010 4.6%





Δm^2_{32} = +2.457 +_0.047 eV^2 1.9%

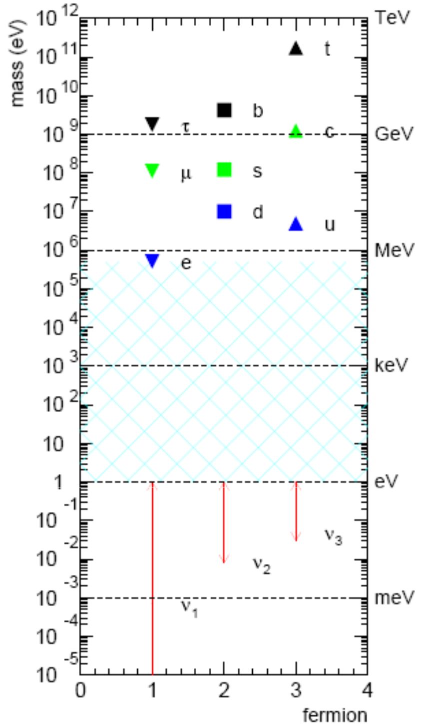
Δm^2_{32} = -2.449 +_0.047 eV^2 1.9%



$\sin^2\theta_{23}$ = Octant instability

Neutrinos: a window beyond the S.M. → G.U.T.

Fundamental questions related to a deeper description of physics and to the evolution of the universe

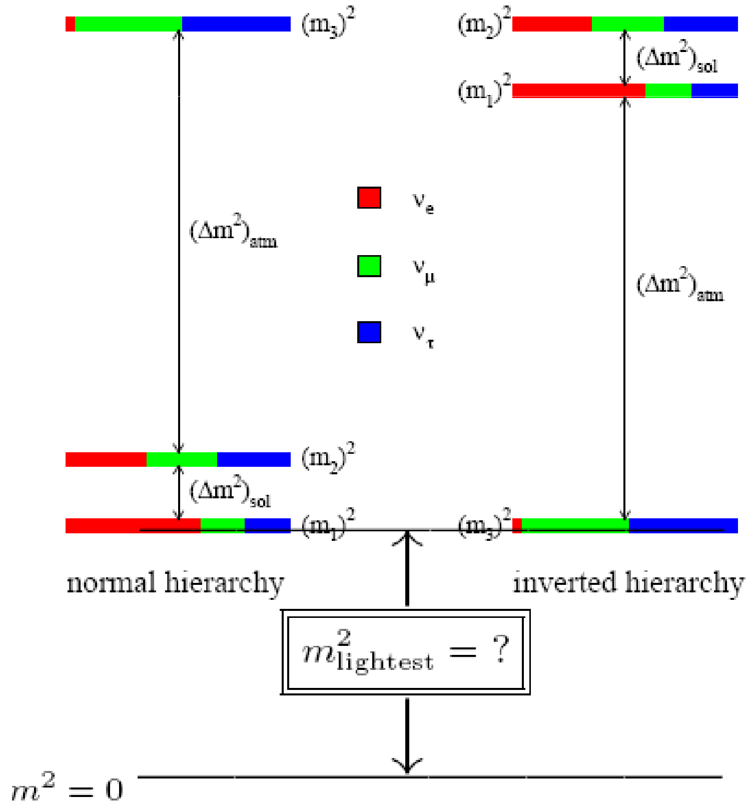


- Why are neutrino masses so small ?
- Why is the mixing matrix so different than the one of the quarks ?

What is this very strange puzzle suggesting us ?

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

- Which is the mass of the lightest state
- Are neutrinos Majorana particles ?
- Which is the hierarchy of the mass eigenstates ?
- Is there CP violation in the neutrino sector ?



CP violation in the neutrino sector can explain the matter/antimatter asymmetry in the universe

An experimental program for the next 30 years (like for CP in quark sector):

Key measurements of neutrino mixing via the study of $\nu_\mu \rightarrow \nu_e$ oscillations:

- θ13
- Matter effects and mass hierarchy
- Search for CP violation

Large θ13 →
next steps accessible with standard beams !

Matter effect

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$

Leading term

Subleading oscillation between the muonic neutrino and the electron neutrino at the Δm^2 of atmospheric neutrinos

$$+\alpha\frac{8J_{CP}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

CP-terms

$$+\alpha\frac{8I_{CP}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$+\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)$$

Solar term

CPV

$$J_{CP} = 1/8 \sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$I_{CP} = 1/8 \cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

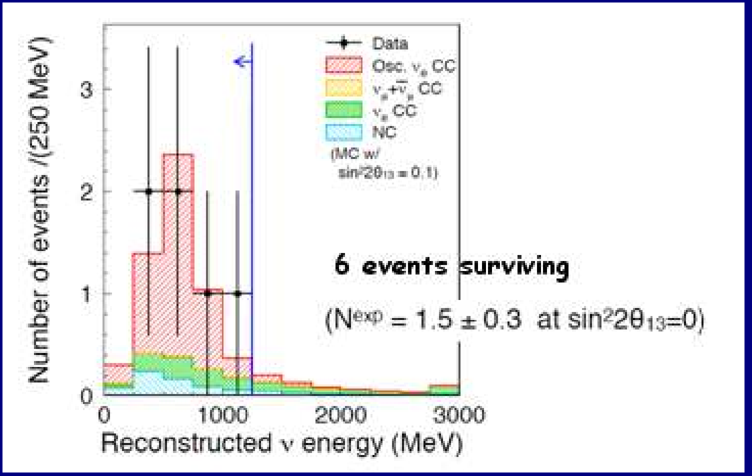
$$\alpha = \Delta m^2_{21}/\Delta m^2_{31},\ \Delta = \Delta m^2_{31} L/4E$$

E_ν dependence

$$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11 \text{ For Earth's crust.}$$

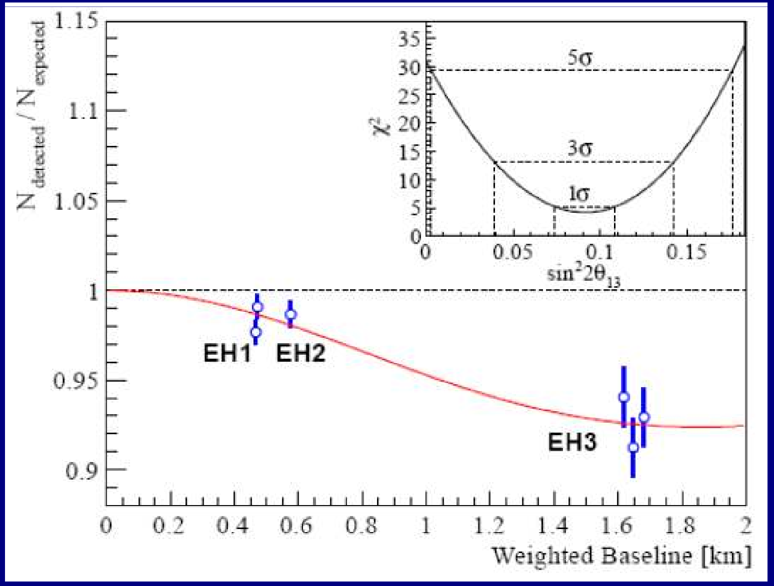
2012: the turning point, $\nu_\mu \rightarrow \nu_e$ oscillations and θ_{13}

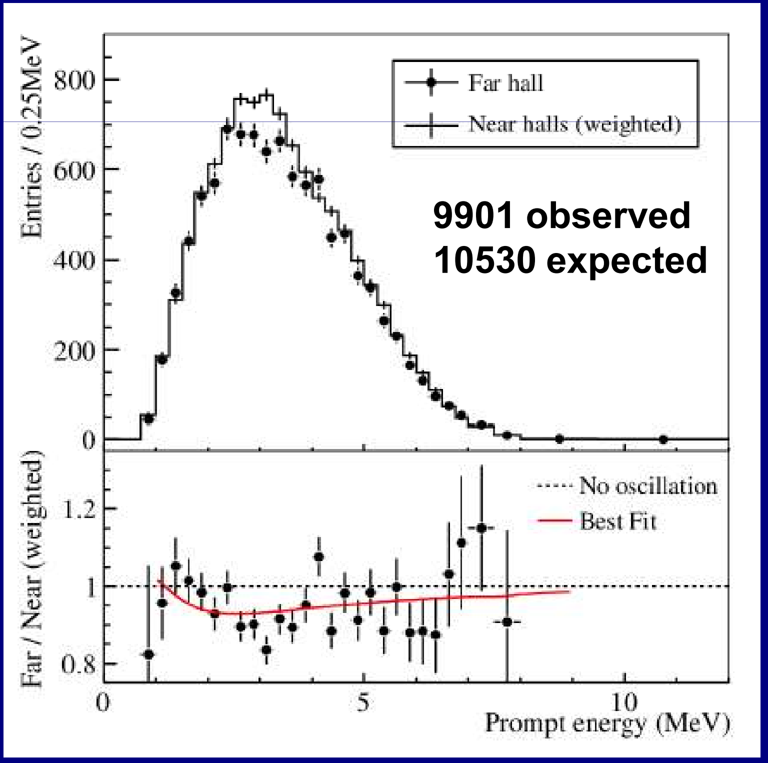
T2K off-axis beam (tuned for osc. max.)
$\nu_\mu \rightarrow \nu_e$ appearance
First result on θ_{13} (June 2011):
6 events observed, 1.5 events bck. → 2.5 σ



March 8th 2012:
Daya Bay reactor anti-neutrinos
$\nu_e \rightarrow \nu_\mu$ (ν_e disappearance)

$$\mathrm{Sin}^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$$

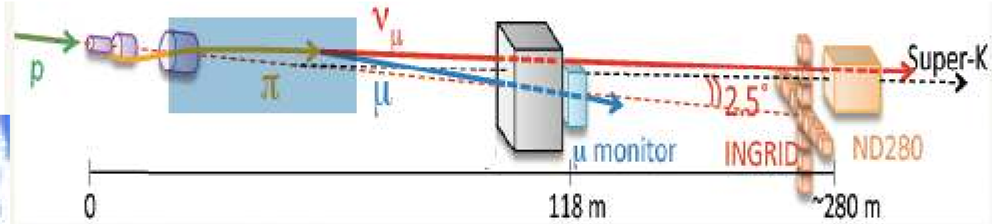


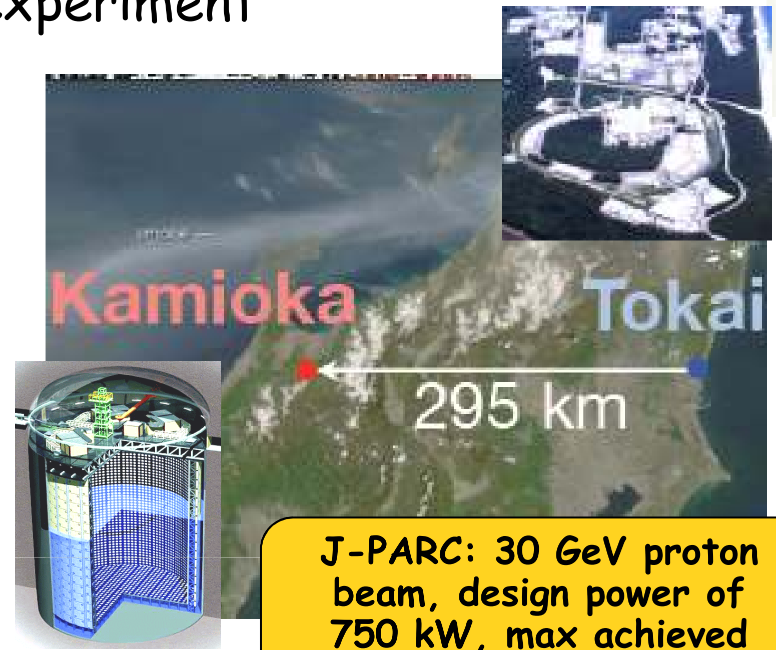


5.2 σ for non-zero θ_{13}

In March 2012 we entered in a new era !!!

The search for θ13: The T2K (Tokai to Kamioka) experiment



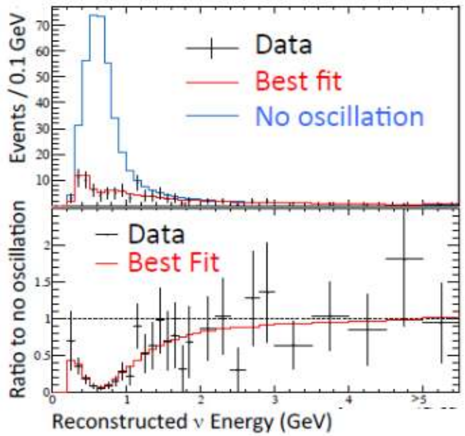


J-PARC: 30 GeV proton beam, design power of 750 kW, max achieved 371 KW

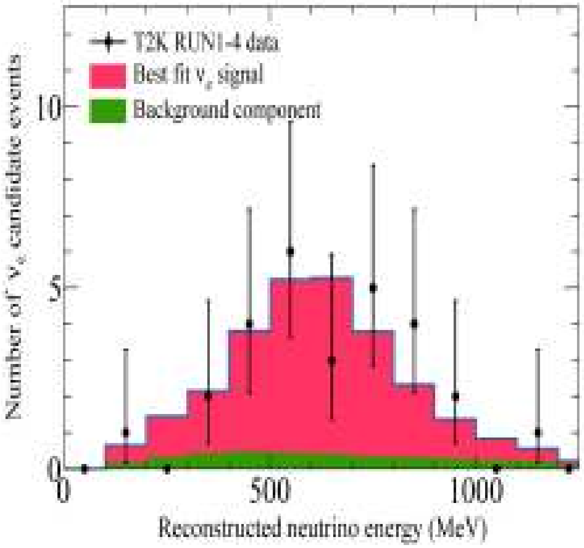
- Baseline 295km, 2.5° off-axis beam tuned to oscillation maximum, <E> ~ 0.6 GeV
- Search for/measure neutrino oscillations:
  $\nu_\mu \rightarrow \nu_e$
  $\nu_\mu \rightarrow \nu_\tau$
- Measurement of θ_{13} in appearance mode
- Disappearance mode: improve measurement of θ_{23}, Δm^2_{23} → is θ_{23} maximal?

$$\sin^2\theta_{23} = 0.514^{+0.0055}_{-0.0056} \text{ (N.H.)}$$
$$\sin^2\theta_{23} = 0.511^{+0.0055}_{-0.0055} \text{ (I.H.)}$$

Θ_{23} measurement further improved in 2015 …



- Most precise measurement of θ_{23} (11%)
- *Phys.Rev.Lett.* **112**, 181801 (2014)



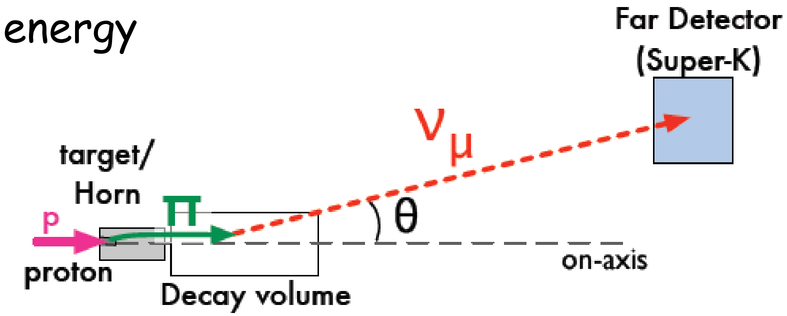
T2K: July 2013
conclusive observation of ν_e appearance from a ν_μ beam:

- **28 ν_e candidate events observed**
- **background 4.64±0.53 events**

7.5 σ significance for non-zero θ_{13}

The off-axis neutrino beam:

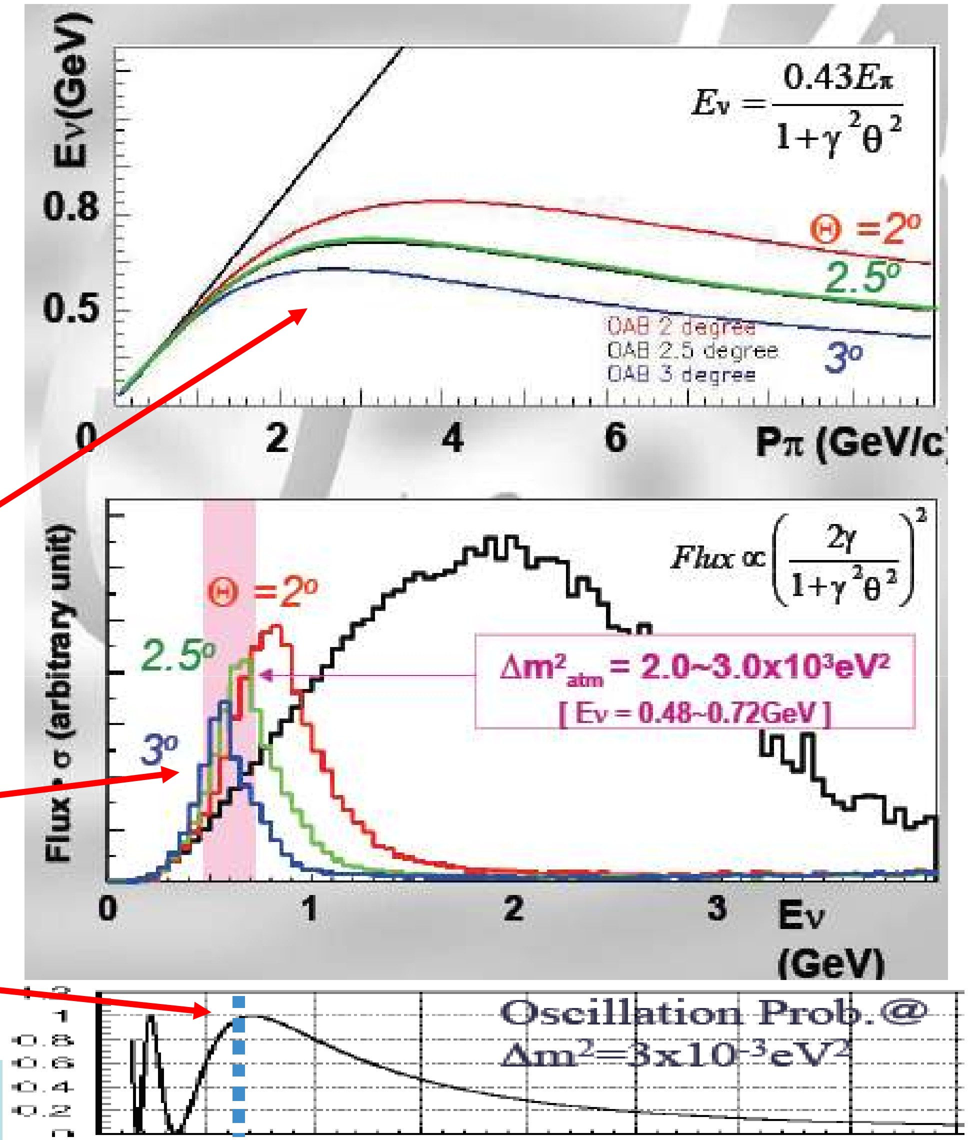
A very brigth idea to produce a tunable intense and narrow-band beam at low energy



Given the pion decay kinematics at off-axis the relation between the pion momentum and the neutrino energy saturates

The flux at low energy is narrow-band and higher than the on-axis flux at the same energy

The energy can be tuned to the first oscillation maximum E~0.6 GeV for 2.5°



→ Most of the beam oscillates, very few ν_μ CC recorded: max disappearance

Small energy tail → low background from NC and ν_e
0.2% ν_e contamination and π° BG

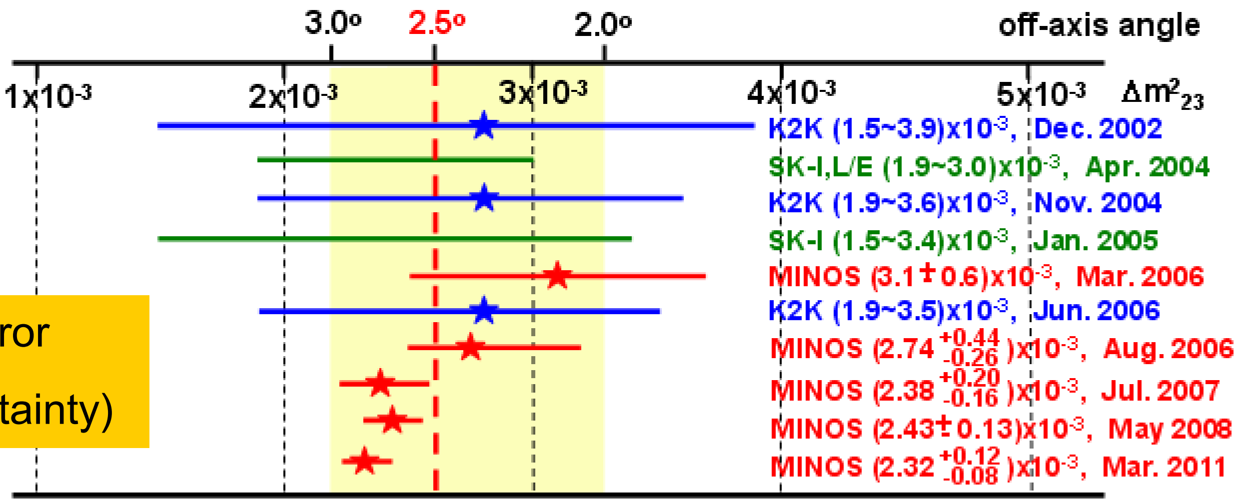
→ max S/B ratio for ν_e search

Important to keep the beam direction stable to have the peak energy stable

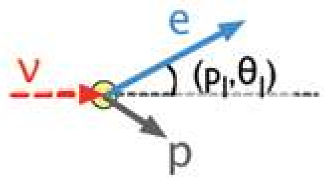
ν_μ disapperance

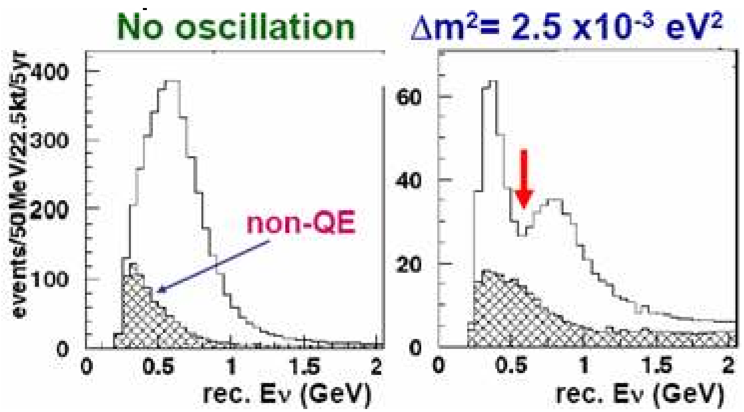
Off-axis angle fixed in 2007

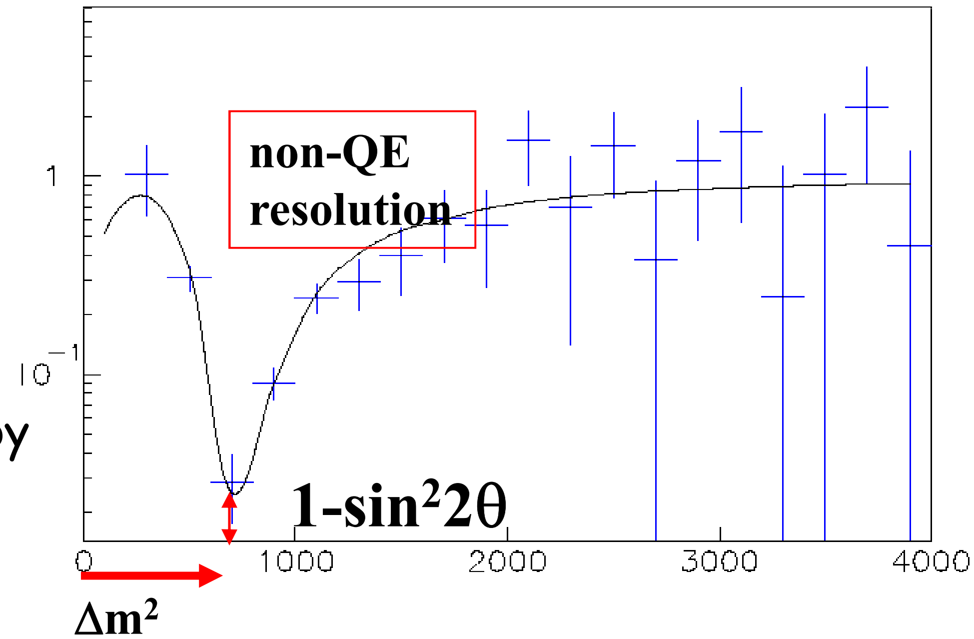
- measure Δm^2_{23} with **10^{-4} eV^2** error
- know if $\sin^2 2\theta_{23} = 1$ (**0.01** uncertainty)



$$E_\nu = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu \cos\theta}$$







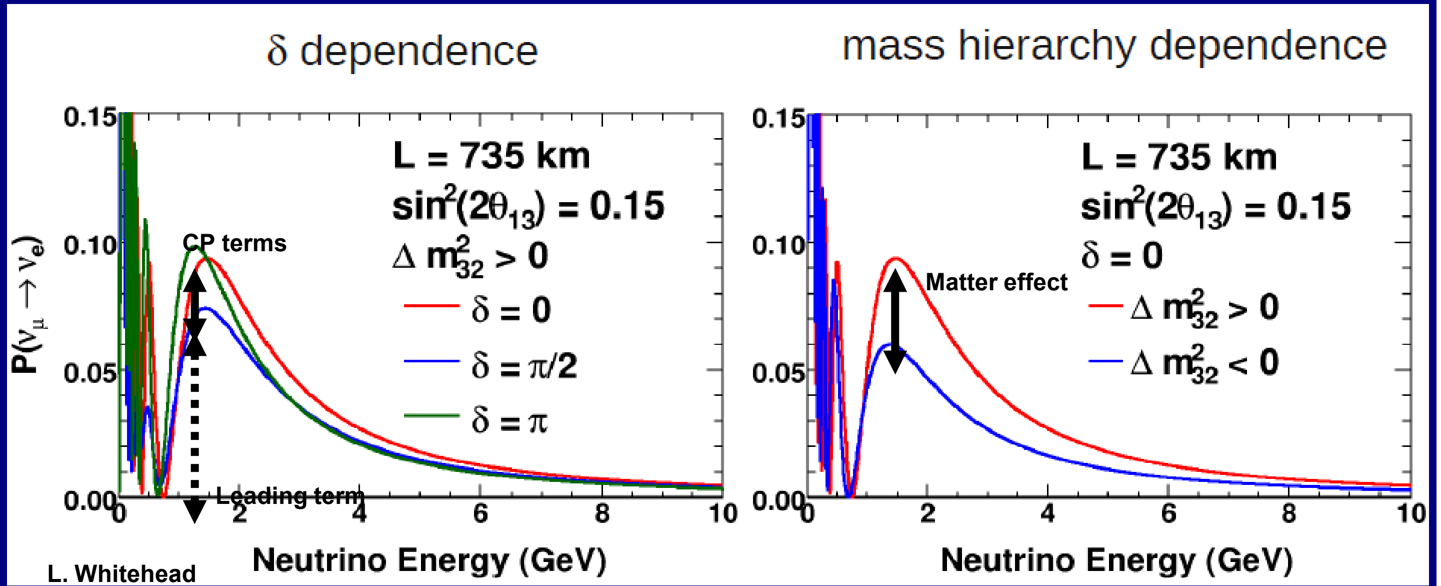
Systematic uncertainty dominated by QE/non-QE ratio (20% syst) which affects the neutrino energy reconstruction in SK

→Near detector has a fundamental role in assessing this ratio

Matter effects and CP violation effects degeneracy

Matter effects mimic CP violation

→ They have to be accurately <u>measured</u> and subtracted in order to look for CP



- <u>Difference between neutrinos and antineutrinos:</u>

$$A \equiv P(\nu_\mu \to \nu_e) - P(\bar\nu_\mu \to \bar\nu_e) =$$

$$16 \frac{a}{\delta m^2_{31}} \sin^2 \frac{\delta m^2_{31} L}{4E} c^2_{13} s^2_{13} s^2_{23}(1-2s^2_{13})$$

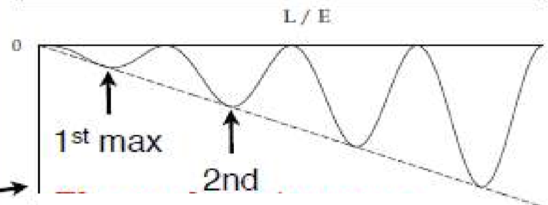
$$-4 \frac{aL}{2E} \sin \frac{\delta m^2_{31} L}{2E} c^2_{13} s^2_{13} s^2_{23}(1-2s^2_{13})$$

Matter terms

$$-8 \frac{\delta m^2_{21} L}{2E} \sin^2 \frac{\delta m^2_{31} L}{4E} s_\delta c^2_{13} s_{13} c_{23} s_{23} c_{12} s_{12}$$

Pure CP-term

$$\left.\frac{P(\nu)-P(\bar\nu)}{P(\nu)+P(\bar\nu)}\right|_{a=0} \approx -\frac{2 s_\delta c_{12} s_{12}}{s_{13}} \cot\theta_{23} \frac{\delta m^2_{21} L}{2E}$$



Amplitude increasing linearly with L/E

- Larger CP asymmetry at second maximum, matter asymmetry dominating around the first maximum, A lot of information is contained in the shape around the first and second maximum

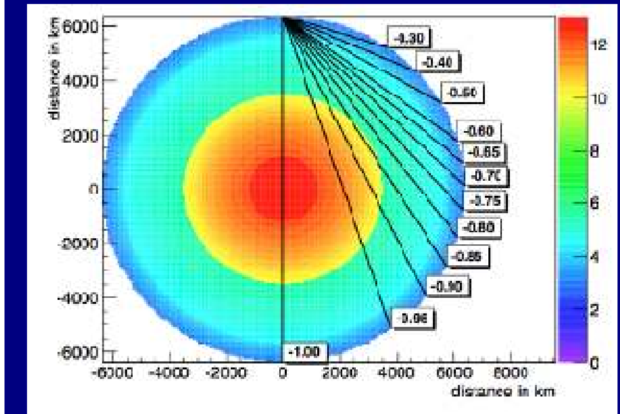
→ Direct measurement of the energy dependence (L/E behavior) induced by matter effects and CP-phase terms, independently for ν and anti-ν, by direct measurement of event spectrum

Addressing mass hierarchy with non accelerator experiments:

Matter effects in atmospheric neutrinos:

Study upward going neutrino flux in bins of energy and cos(θ)

→ Different patterns at low energy

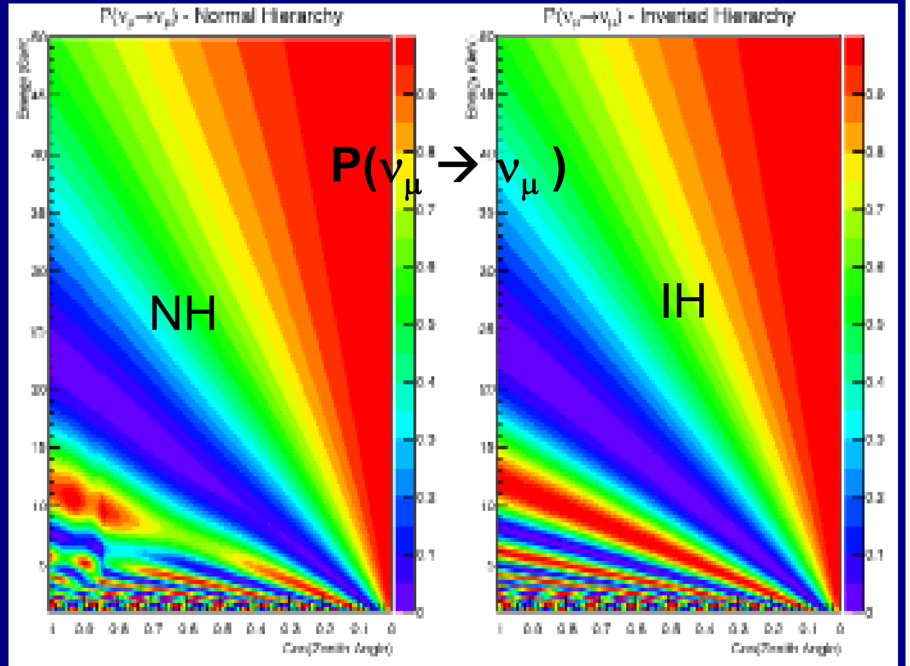


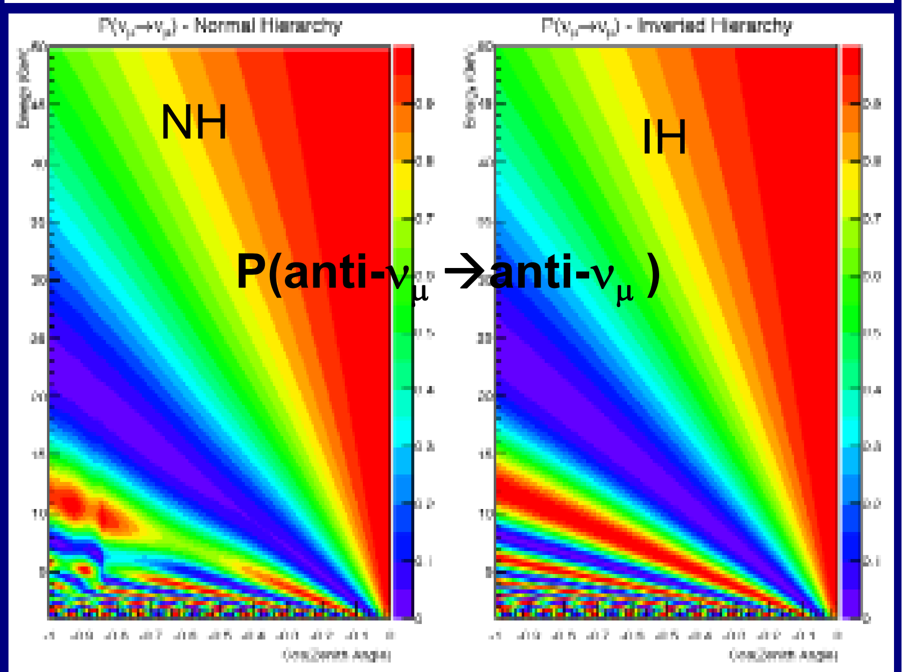
Oscillations probabilities for NH and IH are similar for neutrinos and antineutrinos → if the charge of the muons is not measured the effect is diluted

However there are differences in fluxes and cross sections for neutrinos and antineutrinos and a few % effects can be still measured

Adaptation of the high energy neutrino observatories Icecube and Antares at low energy → Pingu, Orca, higher density of photomultiplier strings

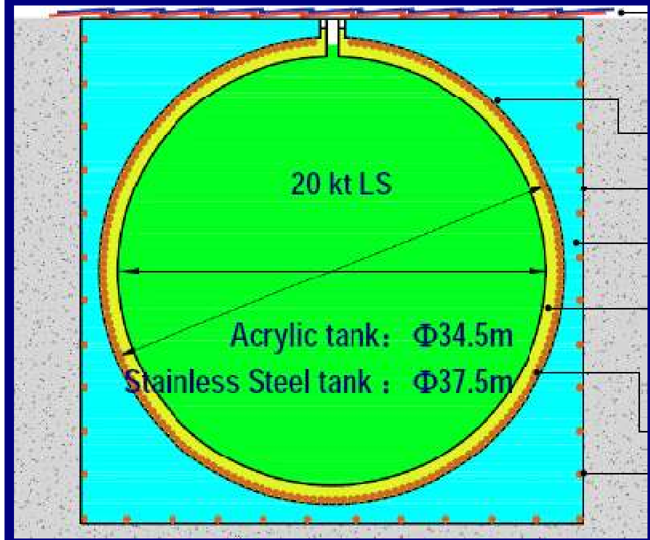
Difficult measurement for flux modelling and detector response to reach ~3σ significance



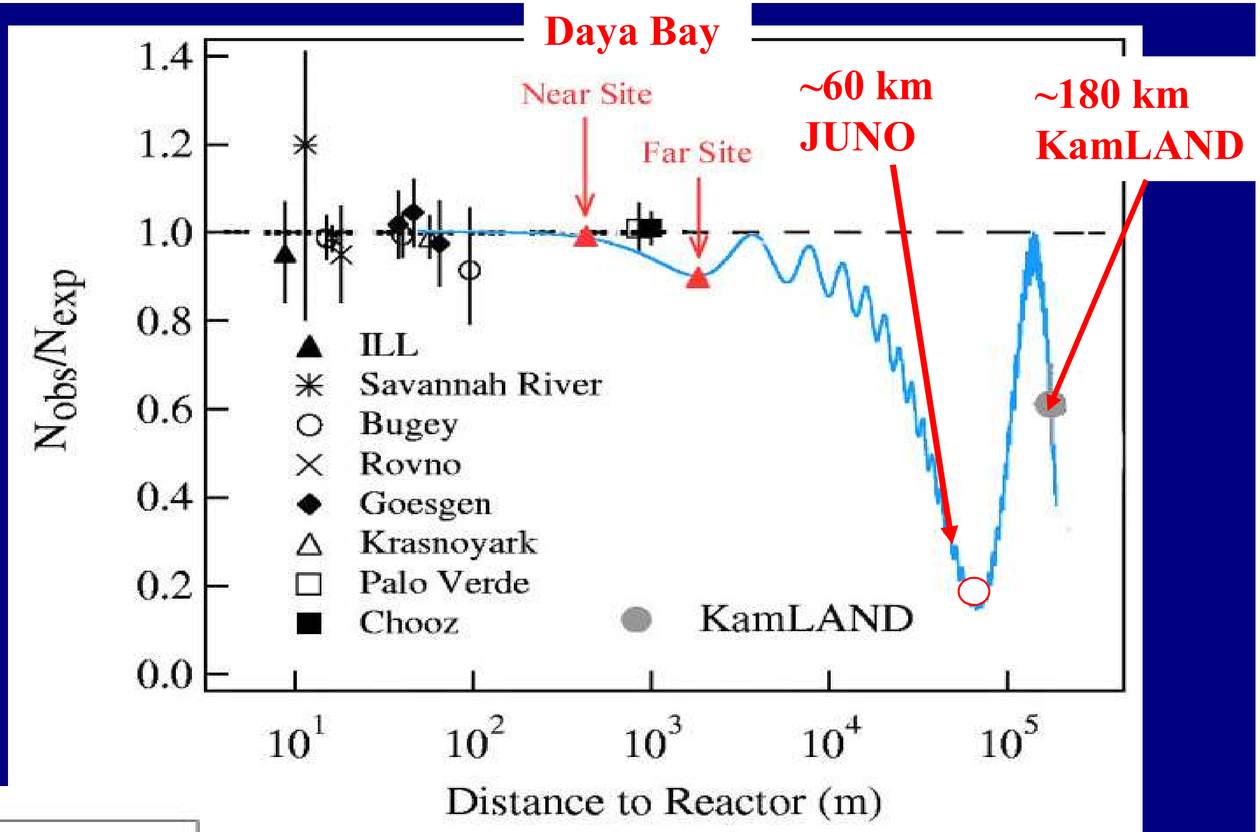


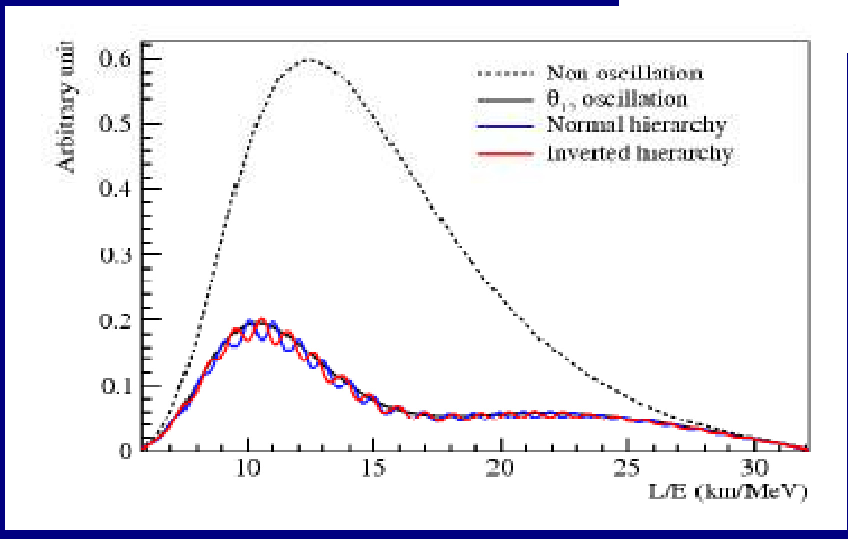
Reactor experiments tuned on solar oscillations wavelength Δm^2_{12}+ θ_{12} (JUNO –RENO50)

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\left(\cos^2 2\theta_{12}\sin^2\frac{\Delta m^2_{13}L}{4E} + \sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{23}L}{4E}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{12}L}{4E}$$



JUNO, expected start in 2020





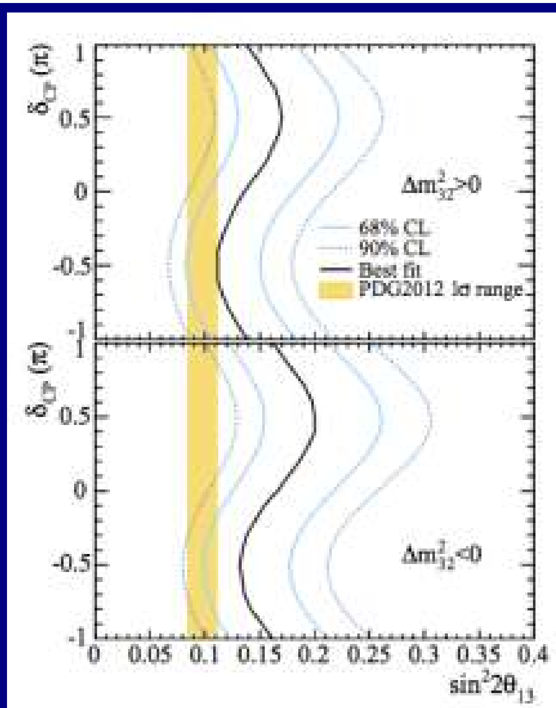
Study of anti-nue disappearance exploiting the interference between the atmospheric and solar terms

→ Shifted patterns in measured neutrino energy spectrum

Requiring exceptional resolution and linearity (<1% precision) to reach ~3σ significance

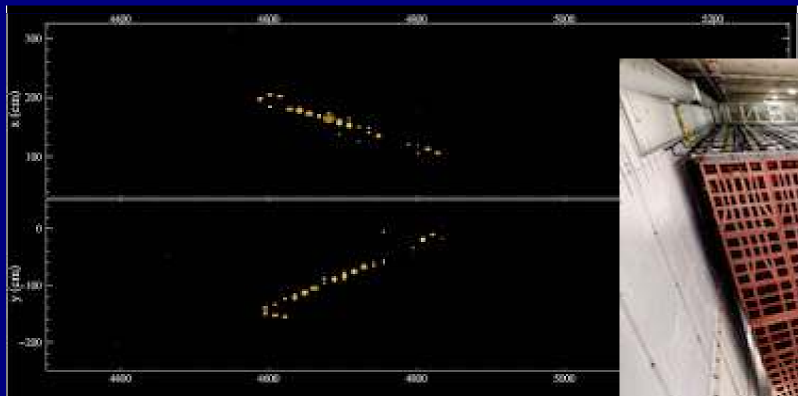
Comparing T2K apperance results, as a function of δ CP with disappearance at reactors (insensitive to CP)

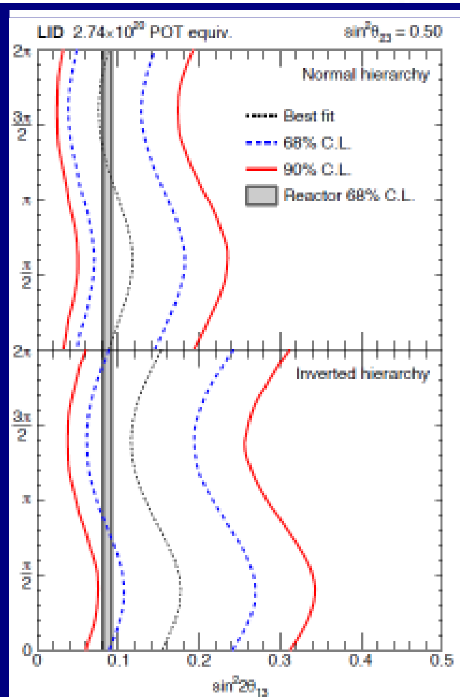
→ Some hint in the direction of $\delta \sim -1/2\pi$ (aka $3/2\pi$)
Current T2K running in anti-neutrino mode



NOVA 14 kton finely segmented liquid scintillator experiment (65% active mass) at 810 km from Fermilab, off-axis 0.84°
Run with neutrinos and anti-neutrinos ~2 GeV

Some complementarities to T2K:
Detector systematics: liquid scintilllator vs WC
Larger matter effects and different interplay among parameters





NOVA first results compatible with reactors, better agreement with NH
The combination of reactors+T2K+NOVA in the next years may yield CP significance at the level of 2-3 σ

The Water Cerenkov approach (extrapolation ~x25 of SK):

- ✓ Large water Cerenkov detector *O*(0.5 Mton), 140k 12" PMT
- ✓ Low energy narrow beam (0.1-1 GeV) → just lepton reconstruction in QE events
- ✓ Short baseline (100-300 km) → no mass hierarchy determination (*needs an external input (atm. neutrinos, other experiments)*
- ✓ New beam needed ~*1.2 MW*

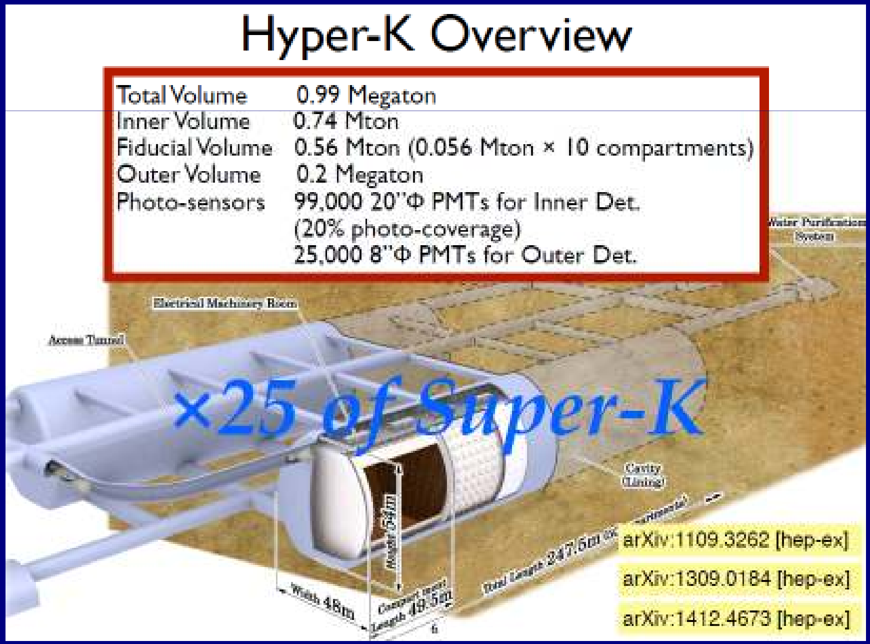
→ Counting only experiment on neutrinos-antineutrinos asymmetry

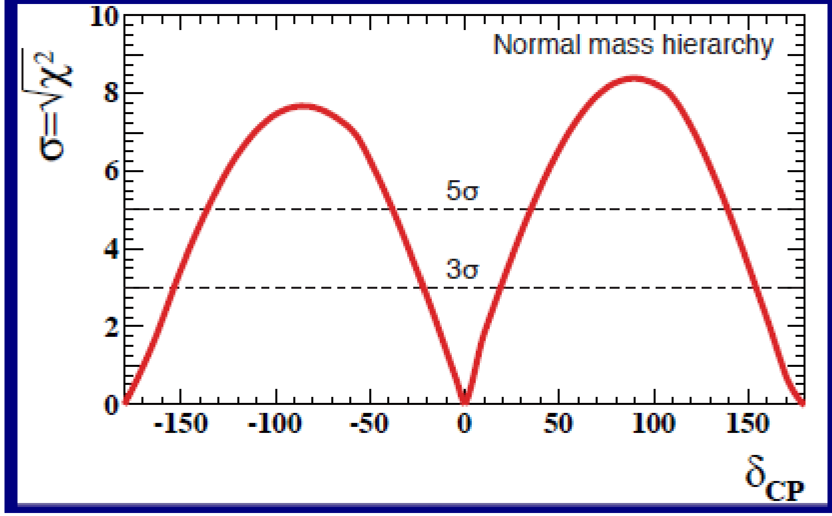
- HyperKamiokande project in Japan

0.56 Mton, 99k PMT 20'', new beam from JPARC (295 km)

Beam neutrinos, Supernovae neutrinos, Search for proton decay

→ Seeking for approval in 2016-2017, with expected start in ~2025

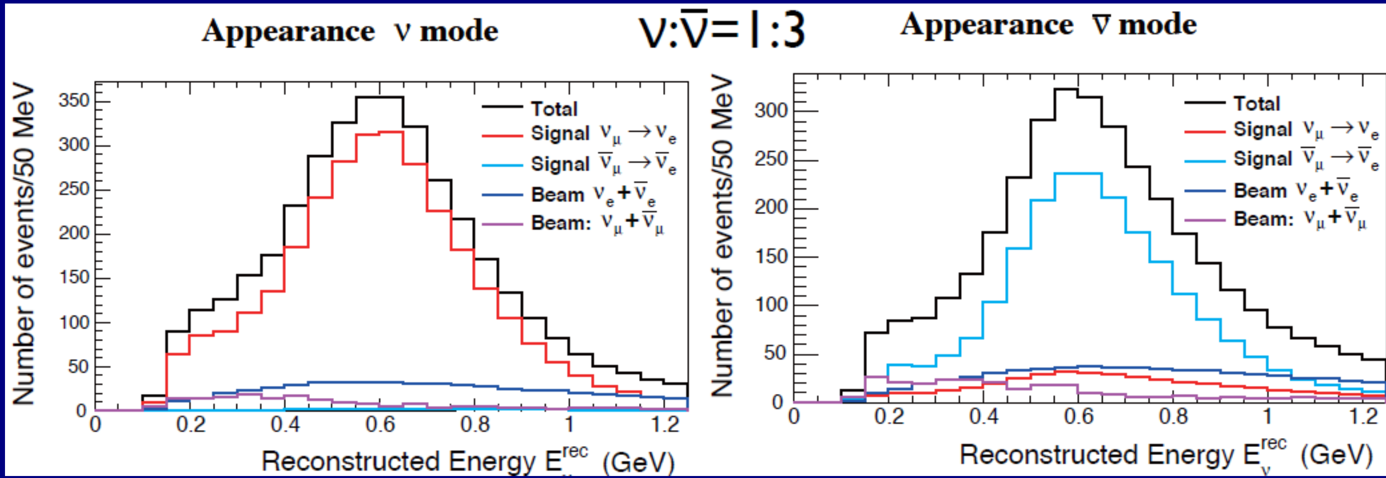




76% (58%) CP coverage 3σ (5σ) if MH know
With 7.5 MW x 10E7 s exposure

Hyperk:

- Continuation of measurements in sub-GeV region
- Mostly « counting , high statistics experiment »
- MH to be known to avoid a systematic bias



HyperK 10 years at 750 kW

	Signal (νμ→νe CC)	Wrong sign appearance	νμ/ν̄μ CC	beam νe/ν̄e contamination	NC
ν	3,016	28	11	523	172
ν̄	2,110	396	9	618	265

Systematic uncertainties based on:

✓ T2K experience

✓ WC ND

✓ study of atmospheric neutrinos control sample in FD

Uncertainty on the expected number of events at Hyper-K (%)

	ν mode		anti-ν mode		(T2K 2014)	
	νe	νμ	νe	νμ	νe	νμ
Flux&ND	3.0	2.8	5.6	4.2	3.1	2.7
XSEC model	1.2	1.5	2.0	1.4	4.7	5.0
Far Det. +FSI	0.7	1.0	1.7	1.1	3.7	5.0
Total	3.3	3.3	6.2	4.5	6.8	7.6

→ total 3.3% uncertainty on nue rate

The Liquid Argon Time Projection Chamber *(C. Rubbia 1977)*

- Homogeneous massive target and ionization detector → electronic bubble chamber

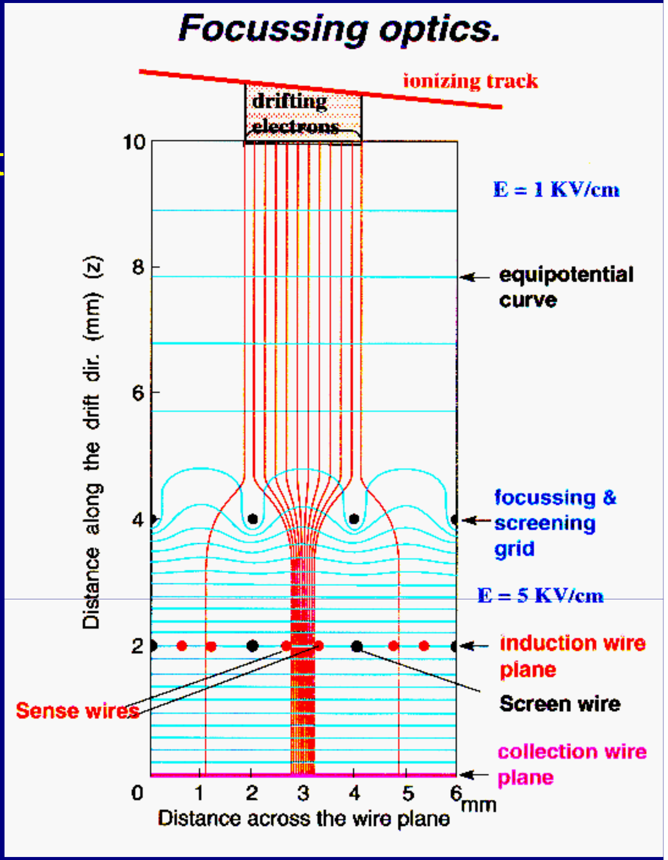
- 3D event reconstruction with ~1 mm resolution, surface readout

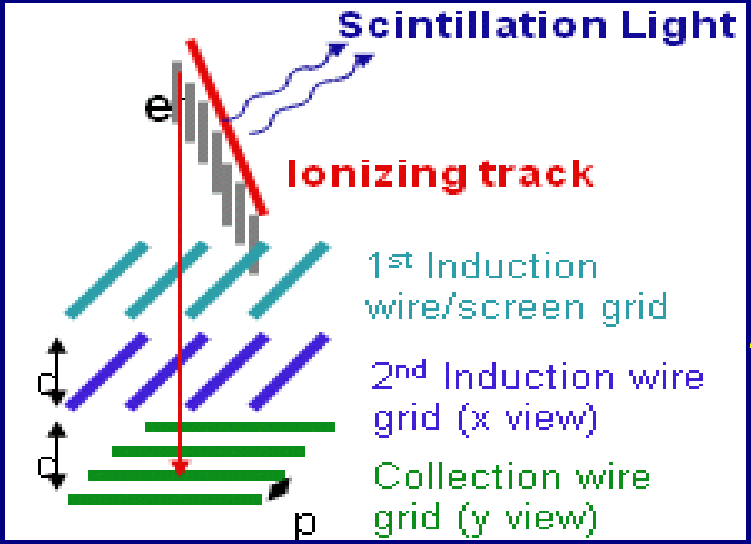
- High resolution calorimetry (electromagnetic and hadronic showers)

- Primary ionization in LAr: 1 m.i.p ~ 20000 e- on 3 mm

- Detection of UV scintillation light in Argon (5000 photons/mm @128 nm) to provide t = 0 signal of the event

Ideal detector for neutrino oscillations, supernovae neutrinos and proton decay





Non-destructive multiple readout with induction planes

z = drift time

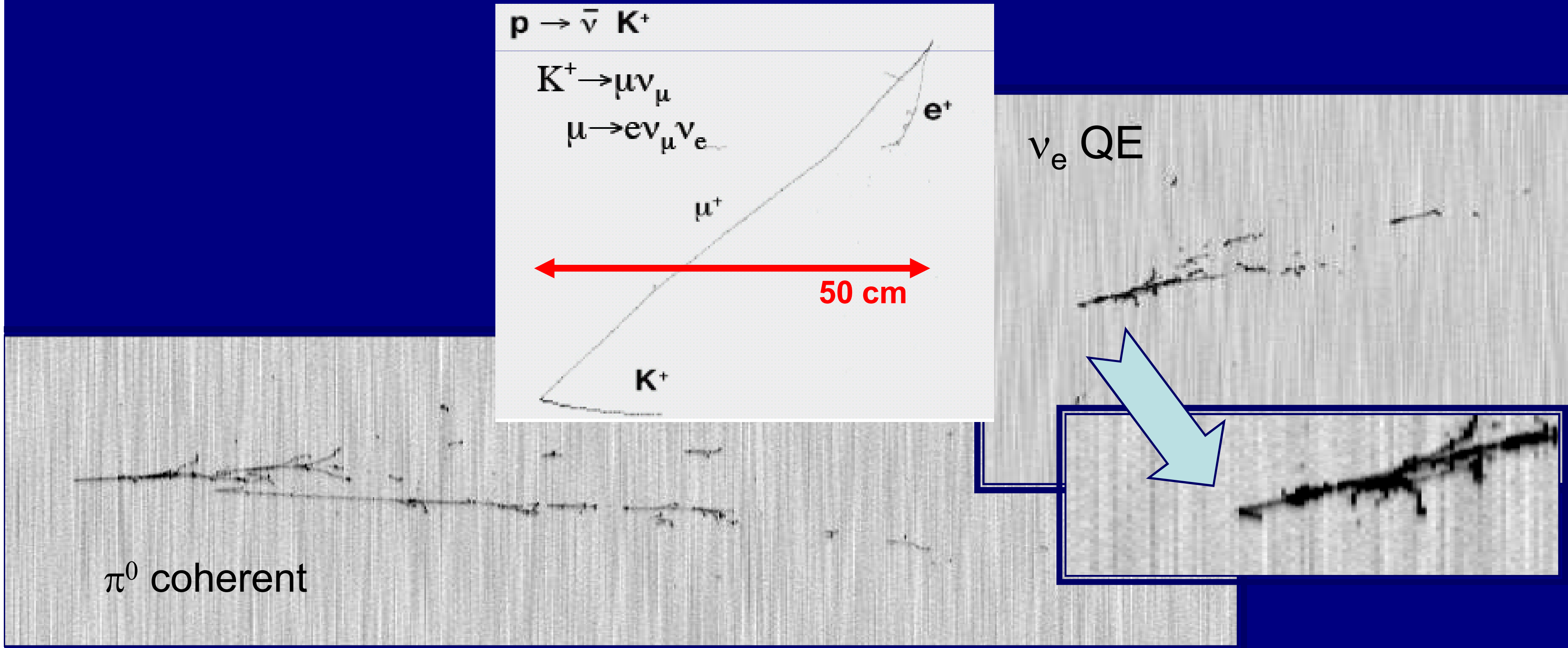
Drift Field: 0.5-1 kV/cm
Drift time:
1.5ms/3m @1 kV/cm

→ drift requiring < 0.1 ppb O_2 equiv. impurities

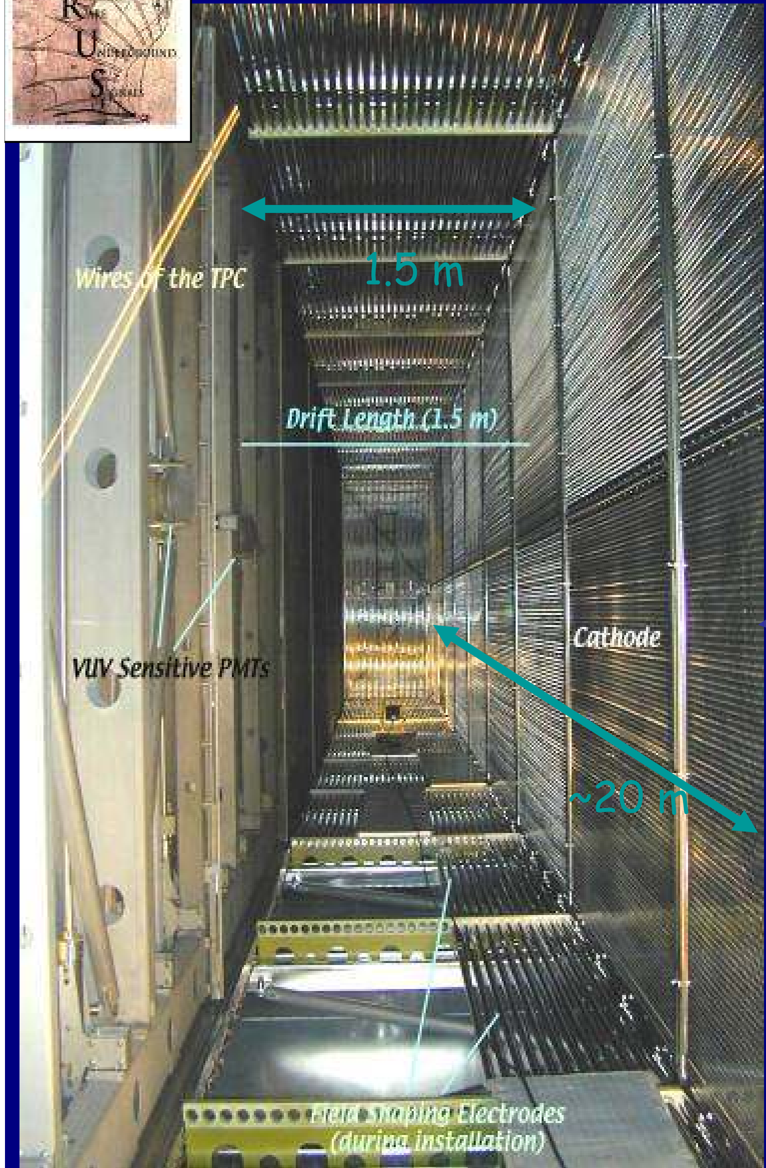
The LAr TPC as an electronic bubble chamber

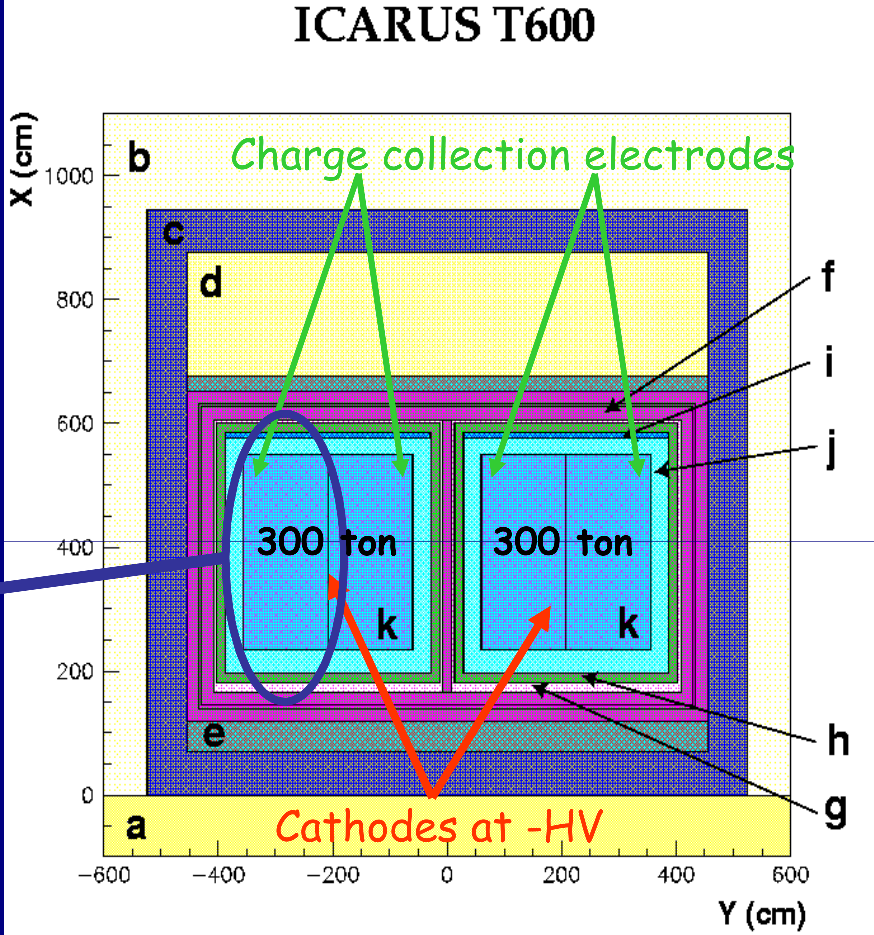
- Large mass, homogeneous detector, low thresholds, exclusive final states
- Tracking + calorimetry (0.02 X0 sampling)
- Electron identification, $\pi 0$ rejection, particles identification with dE/dx

→ Neutrino physics (electron identification, reconstruction of event kinematics, identification of exclusive states, excellent E resolution from sub GeV to multi GeV)
→ Supernovae neutrinos
→ Proton decay search (large mass, particles identification)



The T600 prototype (2001)

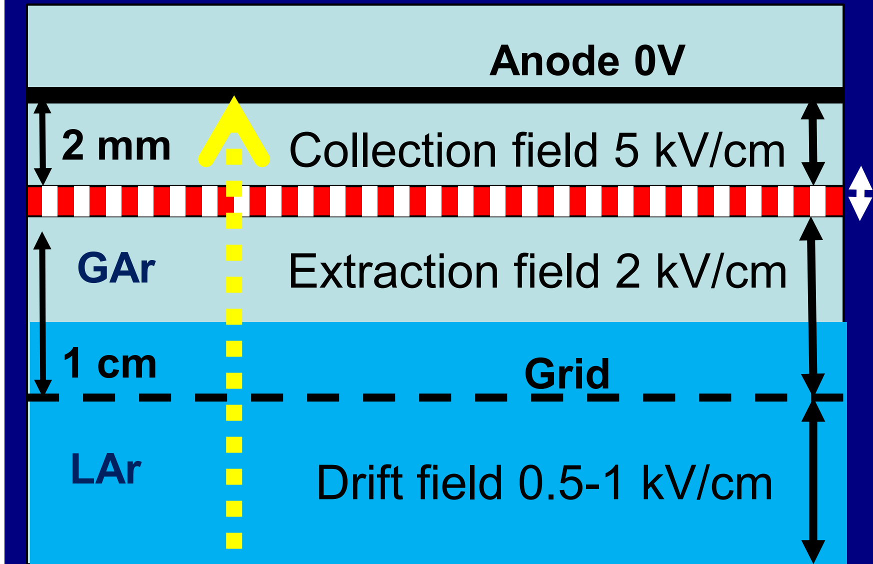


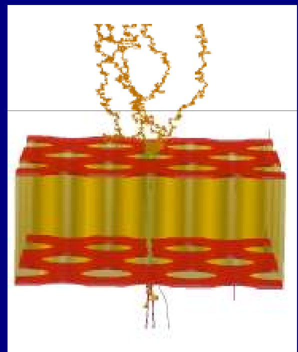


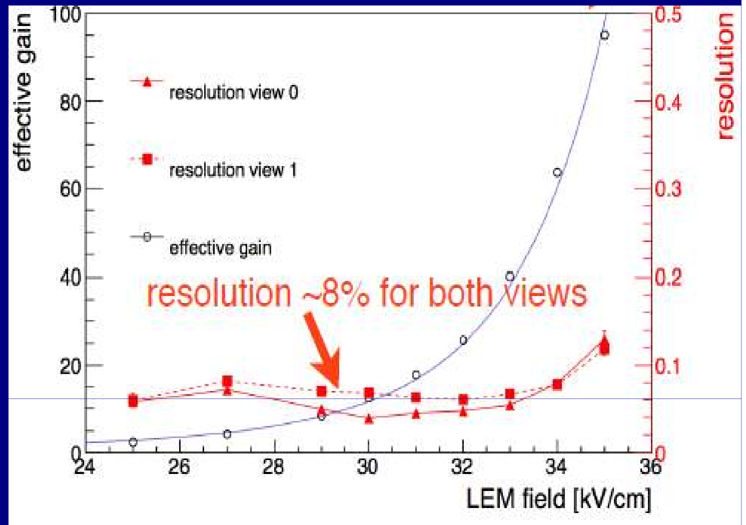
a) rock
b) hall B
c) neutron shield
d) cables-electronics
e) platforms
f) insulation
g) gap
h) container
i) gas phase Ar
j) inactive LAr
k) active LAr

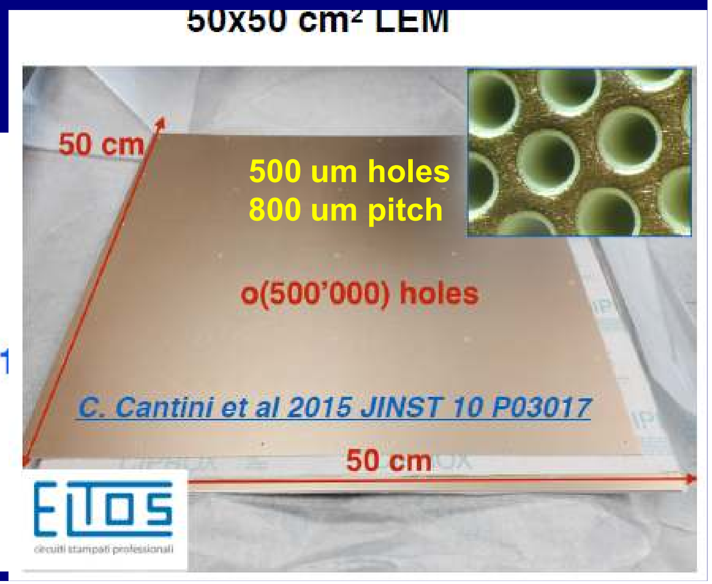
Double-phase readout:

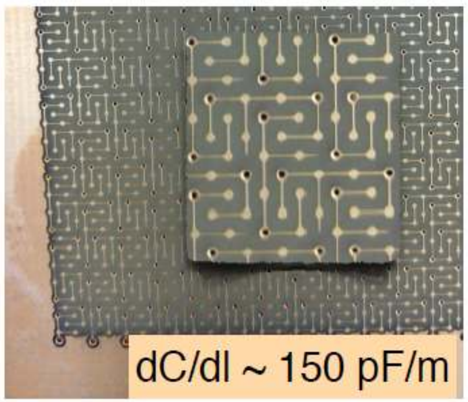
Long drift, high S/N: extraction of electrons from the liquid and multiplication with avalanches in pure argon with micro-pattern detectors like LEM (Large Electron Multipliers)
Tunable gain (~20 minimum), two symmetric collection views, coupling to cold electronics

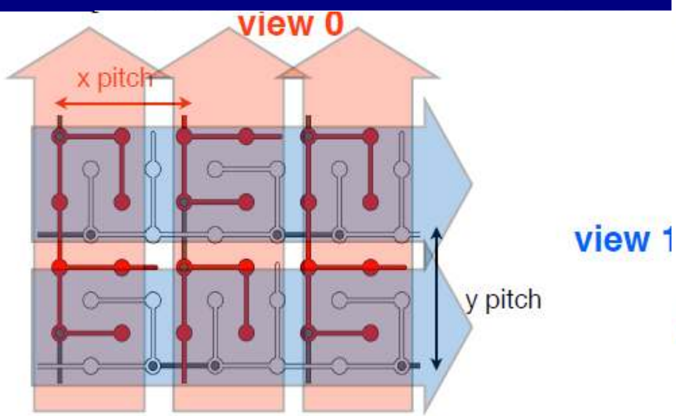


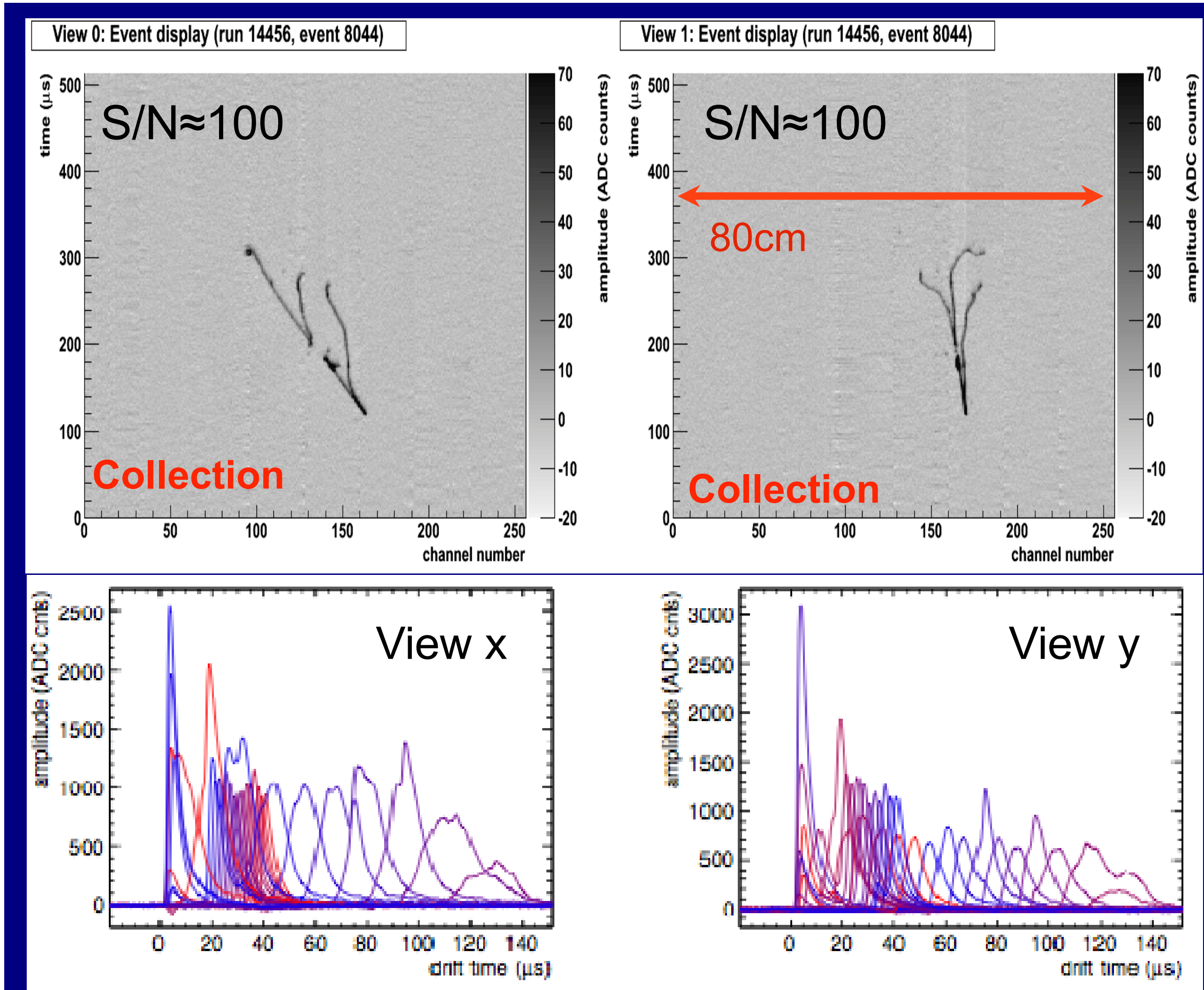












Double-phase prototypes measuring real data events since 6 years with active volumes from 3 to 250 liters:

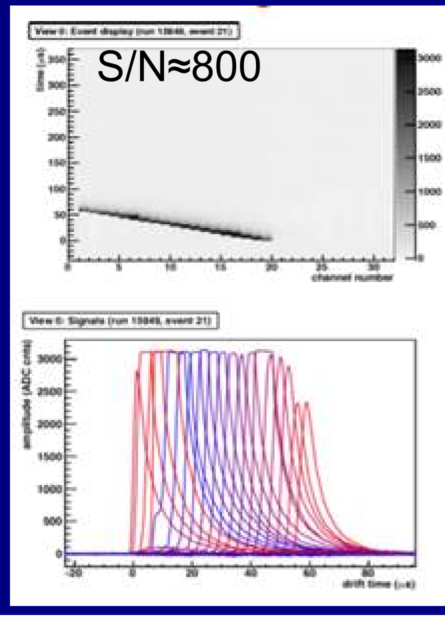
> 15 millions of cosmic events collected in stable conditions S/N~100 for m.i.p. achieved starting from gain ~15

- 3x1x1 m^3 setup at CERN starting operations at the end of 2015
- WA105 6x6x6 m^3 setup will start data taking in 2018

Literature:

NIM A617 (2010) p188-192
NIM A641 (2011) p 48-57
JINST 7 (2012) P08026
JINST 8 (2013) P04012
JINST 9 (2014) P03017
JINST 10 (2015) P03017

Max achieved gain ~200



LAGUNA-LBNO: (2 EU programs 2008-2014)

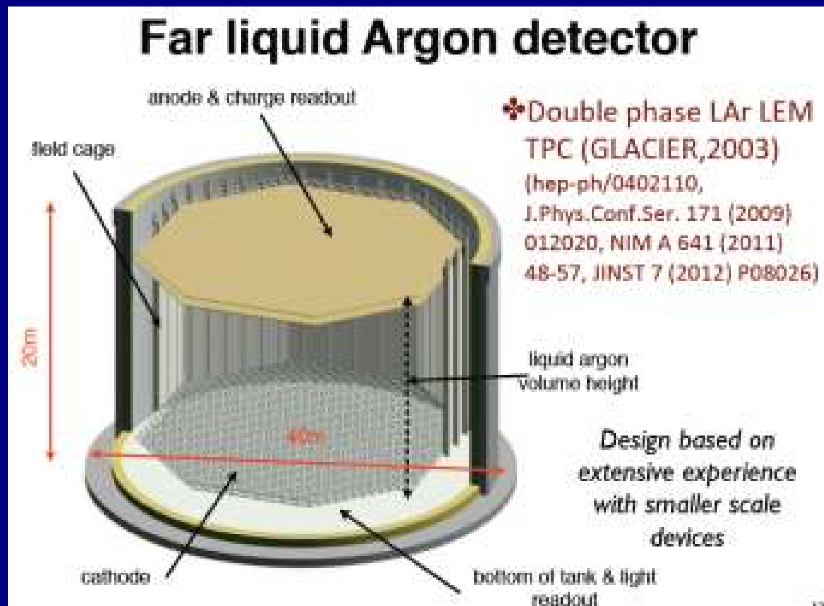
A very long baseline neutrino experiment:
- Determination of neutrino mass hierarchy
- Search for CP violation
- Proton decay
- Atmospheric and supernovae neutrinos

➢ L/E shape, 1st and 2nd max, ν/anti-ν asymmetry
→**Complementary approach to HK:**
CP measurable already with neutrinos

Staged search for CP violation:

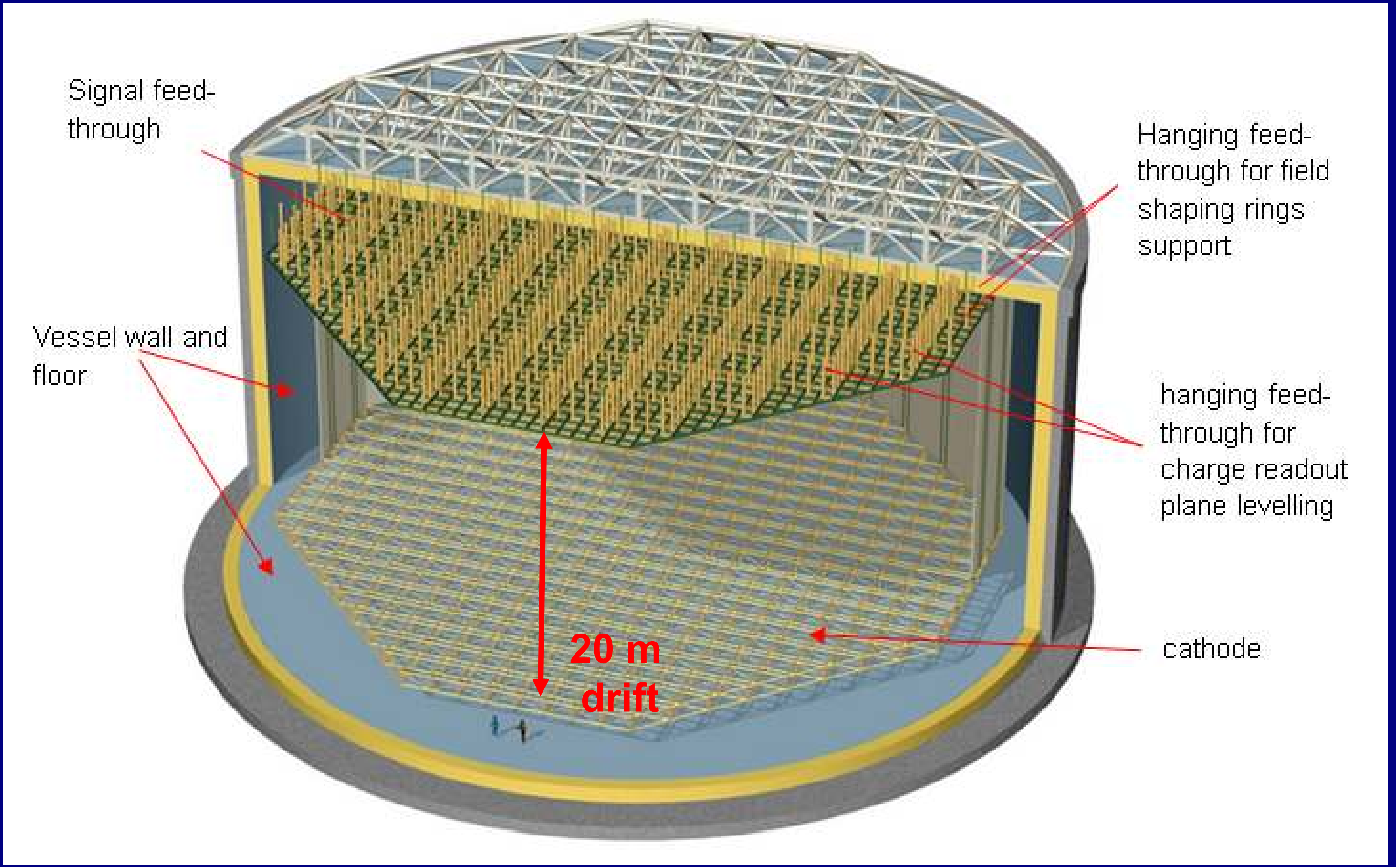
LBNO Phase I:
20 kton double phase LAr TPC,
SPS beam 750 kW, 1.5E20 pot/year
75% nu, 25% antinu
→ **unambiguous mass hierarchy determination (>5σ)**
(median in 2 years, guaranteed in 5 years)
→ **71% (20%) CP coverage at 90% (3σ), <10 years**

LBNO Phase II:
20+50 kton detectors, 2MW HP-PS



LBNO 50 kton

- Drift 20 m
- Cathode span 47 m
- 573444 channels
- Active mass 51.3 kton

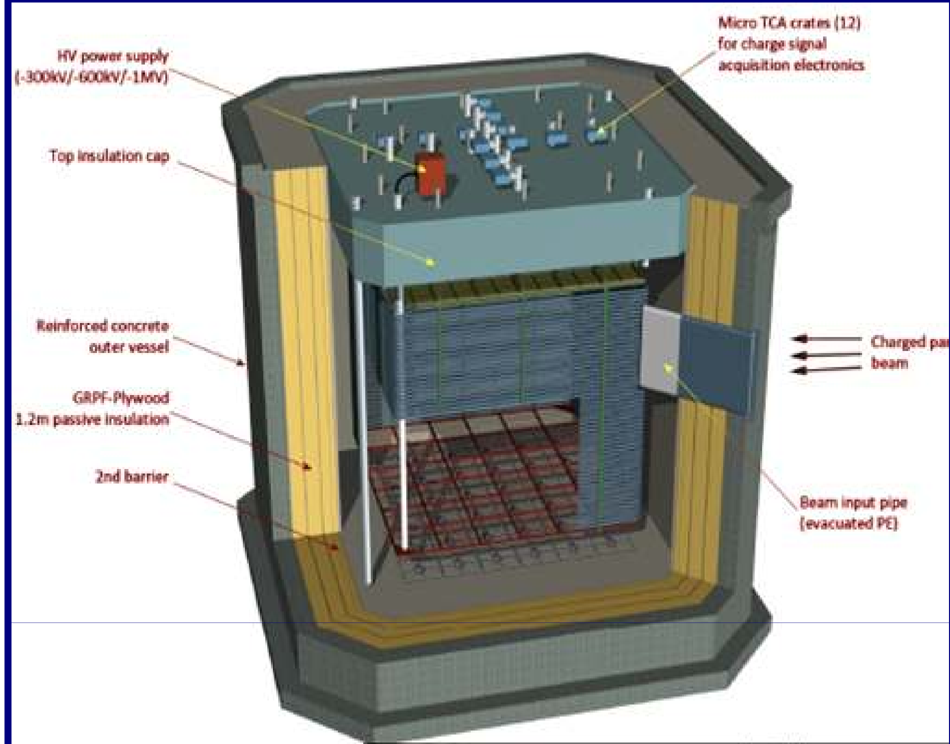


Advantages of double-phase design:

- Anode with 2 collection (X, Y) views (no induction views), no ambiguities
- Readout strips pitch 3.125 mm, 3 m length
- Tunable gain in gas phase (20-100), high S/N ratio for m.i.p. > 100, <100 KeV threshold, min. purity requirement 3ms → operative margins vs purity, noise
- Long drift projective geometry: reduced number of readout channels
- No materials in the active volume
- Accessible and replaceable cryogenic FE electronics, high bandwidth low cost external uTCA digital electronics

The LBNO-DEMO/WA105 experiment at CERN

WA105



Liquid argon density	T/m^3	1.38
Liquid argon volume height	m	7.6
Active liquid argon height	m	5.99
Hydrostatic pressure at the bottom	bar	1.03
Inner vessel size (WxLxH)	m^3	8.3 × 8.3 × 8.1
Inner vessel base surface	m^2	67.6
Total liquid argon volume	m^3	509.6
Total liquid argon mass	t	705
Active LAr area	m^2	36
Charge readout module (0.5 x0.5 m^2)		36
N of signal feedthrough		12
N of readout channels		7680
N of PMT		36

→ 1/20 of 20 kton LBNO detector

6x6x6m^3 active volume, 300 ton , 7680 readout channels, LAr TPC (double phase+2-D collection anode): DLAr
Exposure to charged hadrons, muons and electrons beams (0.5-20(10) GeV/c)

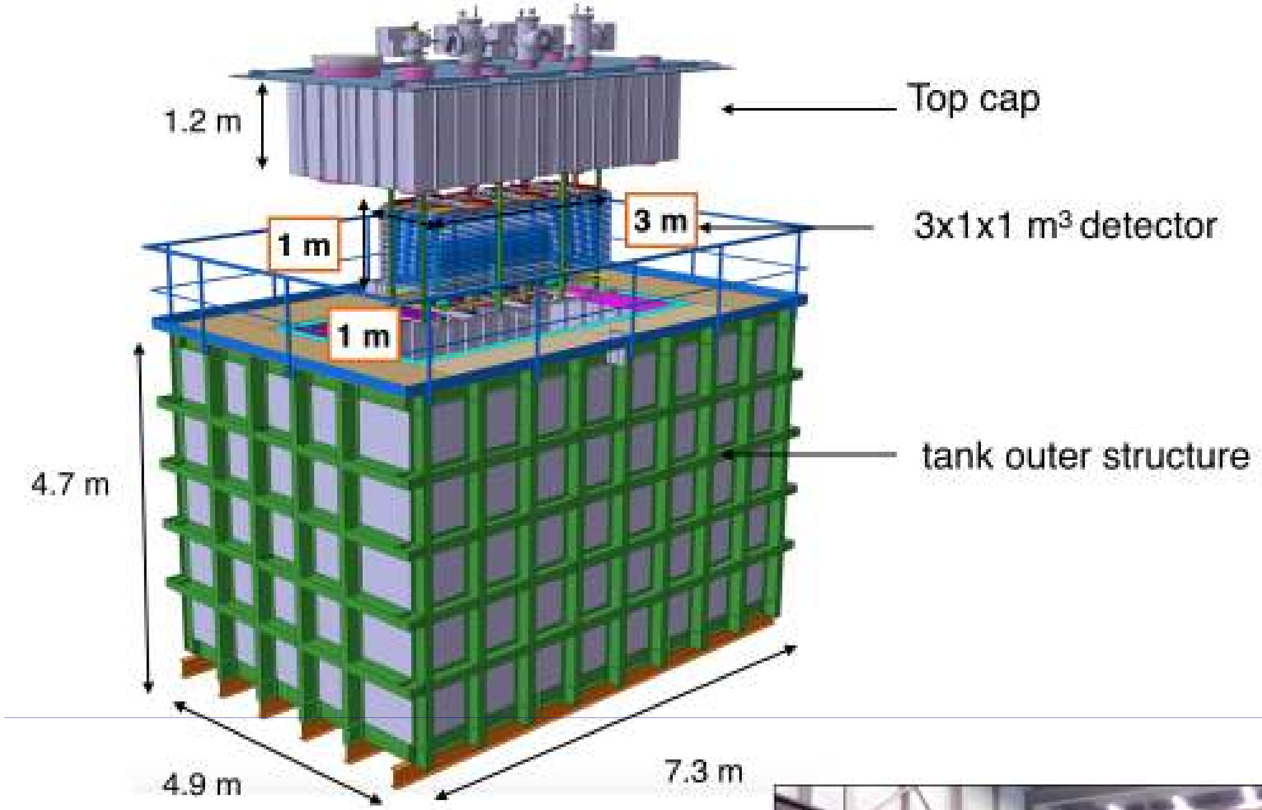
Full-scale demonstrator of all innovative LAGUNA-LBNO technologies for a large LAr detector:

- **LNG tank construction technique (with non evacuated vessel)**
- **Purification system**
- **Long drift**
- **HV system 300-600 KV, large hanging field cage**
- **Large area double-phase charge readout**
- **Accessible FE and cheap readout electronics**
- **Long term stability of UV light readout**

Assess performance in reconstructing hadronic showers (most demanding task in neutrino interactions):

- **Measurements in hadronic and electromagnetic calorimetry and PID performance**
- **Full-scale software development, simulation and reconstruction to be validated and improved**

Installation in the CERN NA EHN1 extension, data taking in 2018
→ Fundamental step for the construction of a large LAr detector



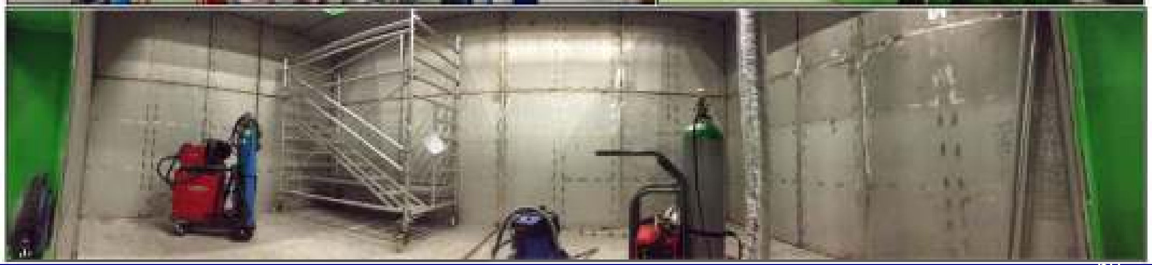
The 3x1x1 Vessel

Tank outer structure: completed

Panels installation: completed
August 9th 2015

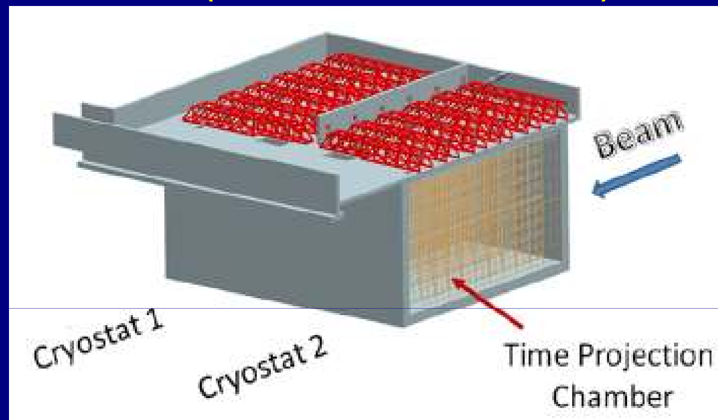
TOP cap closure: November 2015

Gas purity measurement:
December 2015



The Liquid Argon approach:

- Main option in LAGUNA-LBNO:
- ✓ Liquid argon TPC *O*(20kton)
- ✓ High energy (>1 GeV) beam, all final states accessible
- → L/E pattern and <u>second oscillation maximum</u>
- ✓ Long baseline (>1000 km) → mass hierarchy measurement (2300km for LBNO)



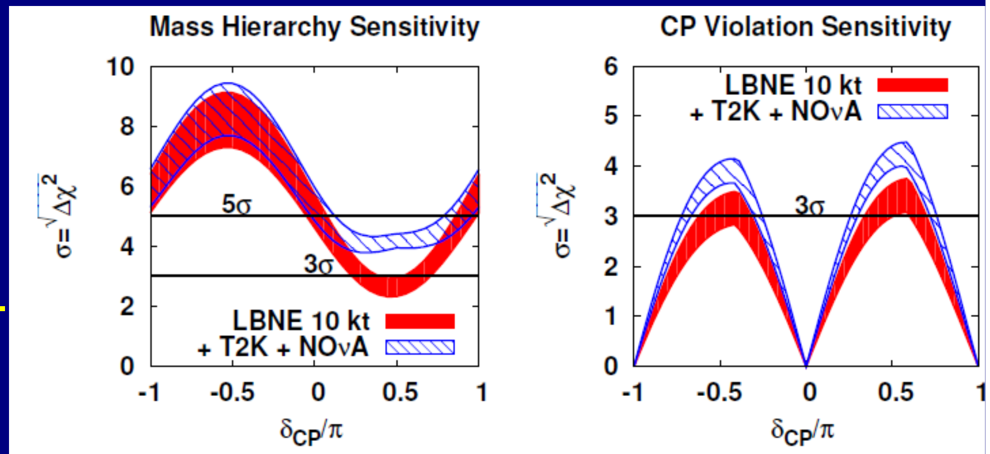
- LBNE project in USA

→ First phase 2022 (~900 M$):
700 kW beam from FNAL to Homestake,
1300 km → limited matter effects
10 kton LAr far detector <u>on surface</u>
<u>no near detector</u>

(→ marginal outcome of Phase I)

- Sensitivity from only first oscillation max.
- Needs very small syst. errors.

Further stages: underground far detector
35 kton, 2.3 MW beam (Project X)



Can resolve MH with $\geq 5/4\sigma$ for 50%/all δ_{cp} combined

Can resolve CPV with $\geq 3\sigma$ for 45% δ_{cp} combined

LBNO physics strategy

- Select a very long baseline (2300km and optimized site for installation) to explore the L/E pattern predicted by the 3 flavor mixing mechanism over the 1st and 2nd max.
- Staged experiment adjusting the beam and detector mass on the bases of the findings of the first phase, most efficient use of resources:

- **Phase I (LBNO20)**

  24 kton DLAR + SPS beam (700 kW, 400 GeV/c), 15E20 pot, 25% antinu
  Guaranteed 5σ MH determination + 46% CP coverage at 3σ + proton decay + astroparticle physics

- **Phase II (LBNO70)**

  70 kton DLAR + HPPS beam (2 MW, 50 GeV/c) 30E21 pot, 25% antinu or Protvino beam, 80% (65%) CP coverage at 3σ (5σ) + proton decay + astroparticle physics

- Complementarity to HyperK (numu vs anti-numu at first max, 300 km) → L/E dependence at 2300 km, 25% antinumu. matter effects

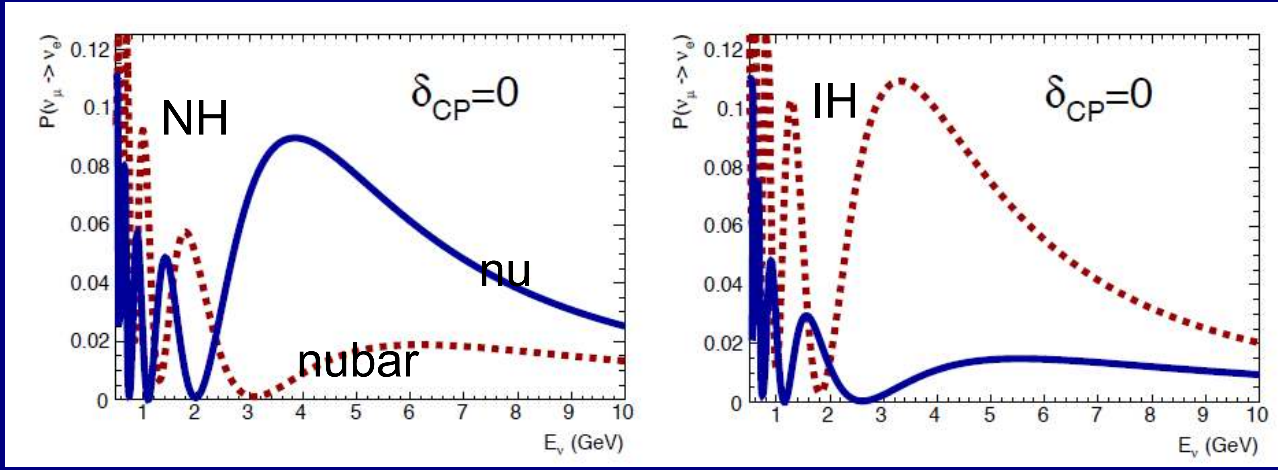
- L/E pattern measurement releases requirements on systematic errors related to the rate normalization at the first maximum

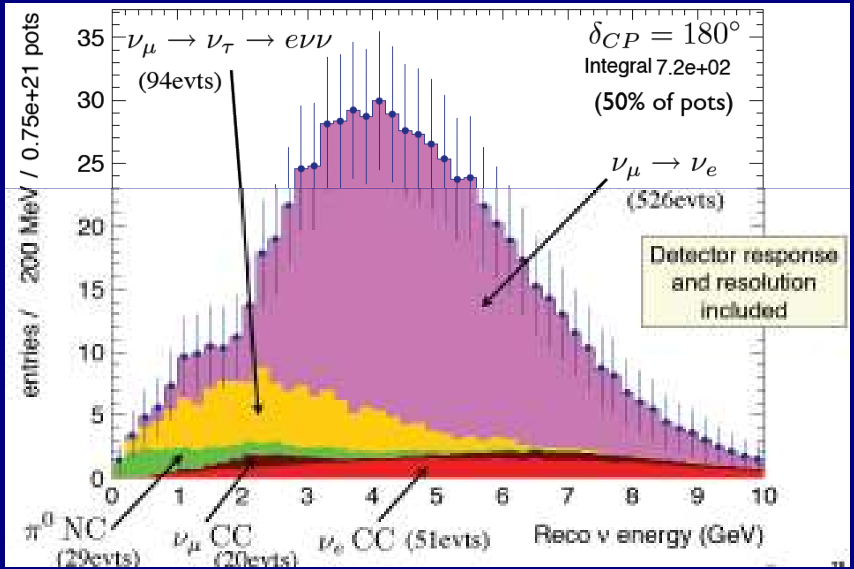
→ Guarantee MH at 5σ and incremental CP coverage satisfying the P5 requirements

Unambiguous mass hierarchy determination

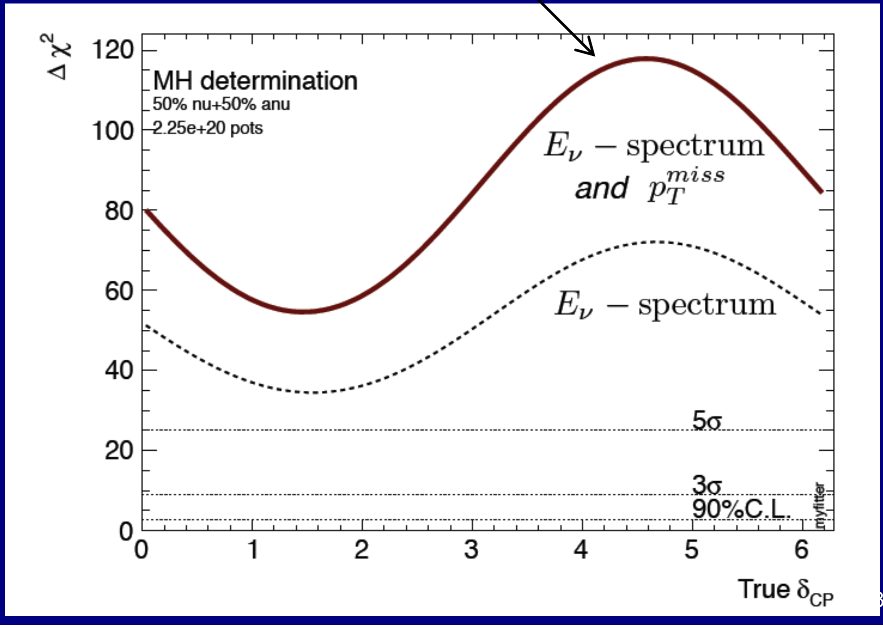
L/E shape + nu/nubar

→unique worldwide sensitivity



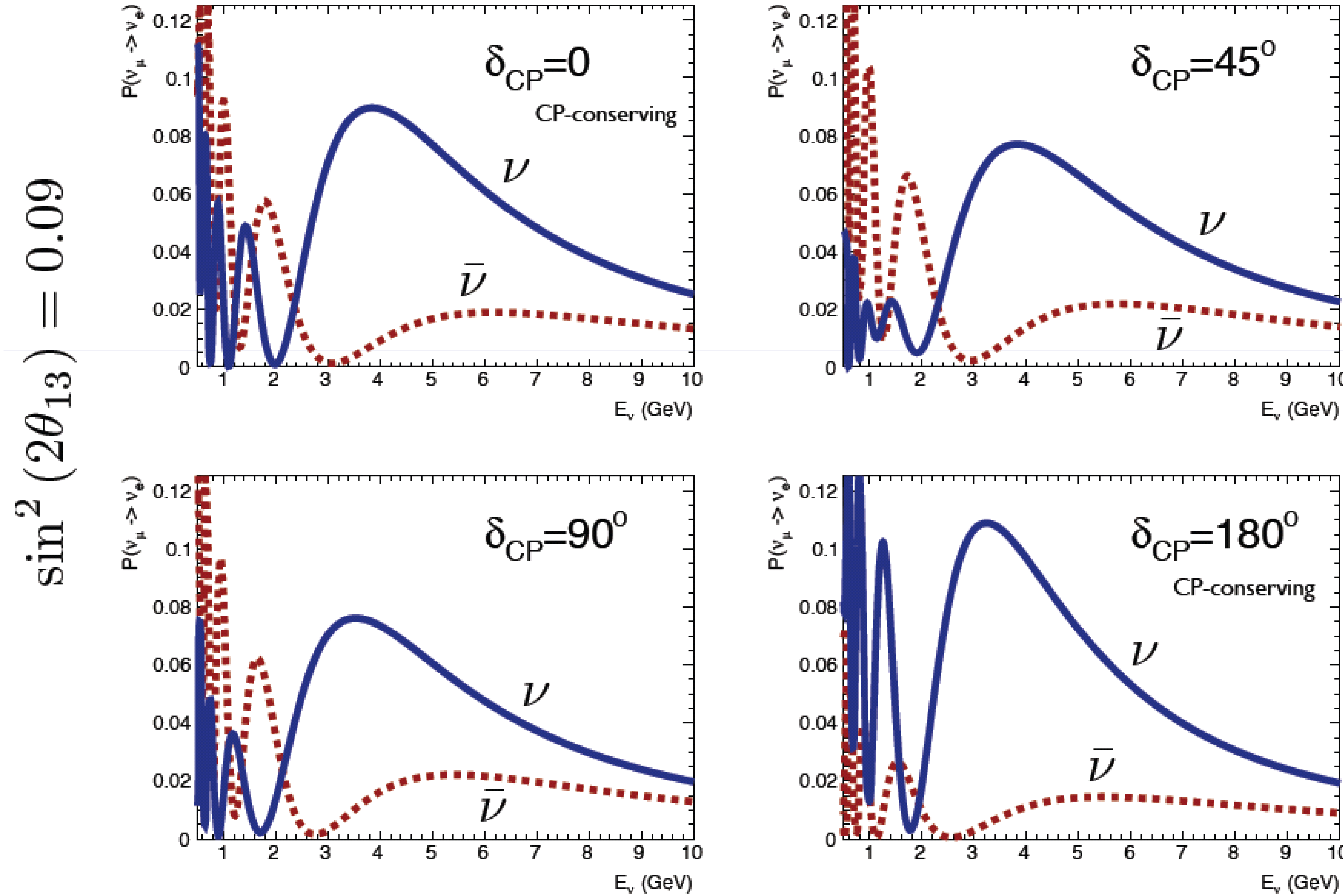


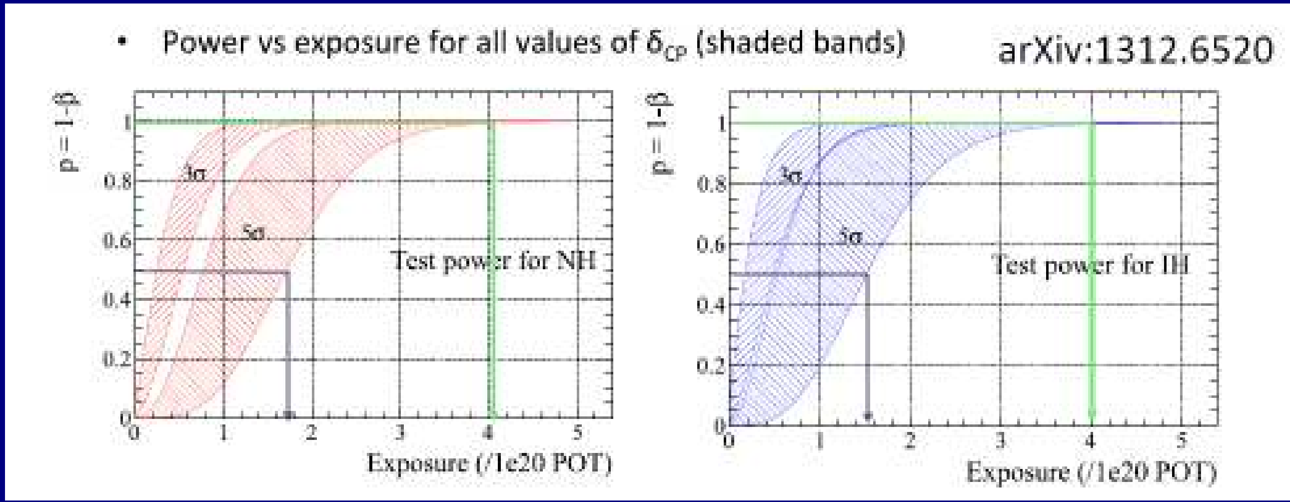
With additional constraint on tau production rate



CERN-Pyhäsalmi: spectral information $\nu_\mu \to \nu_e$

★Normal mass hierarchy L=2300 km

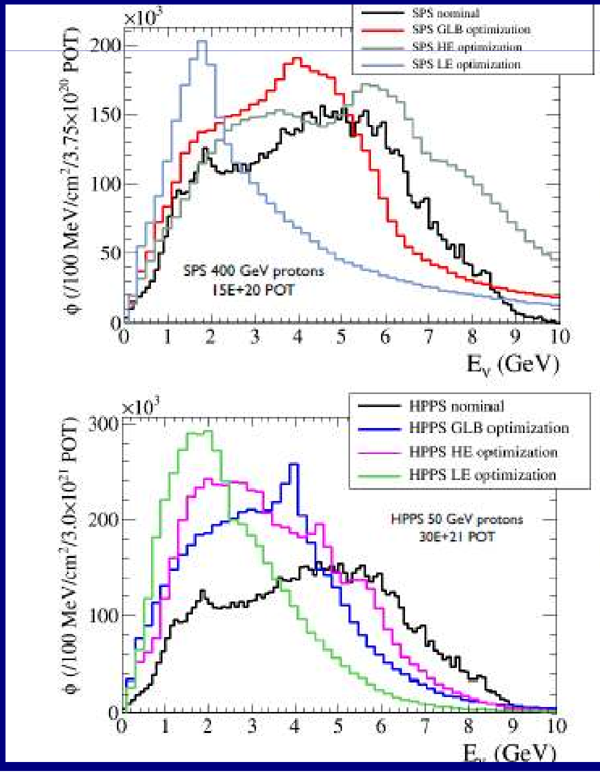


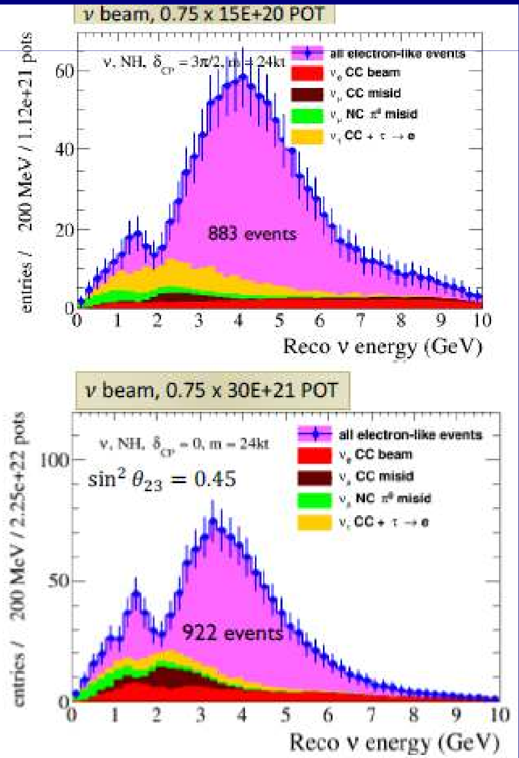


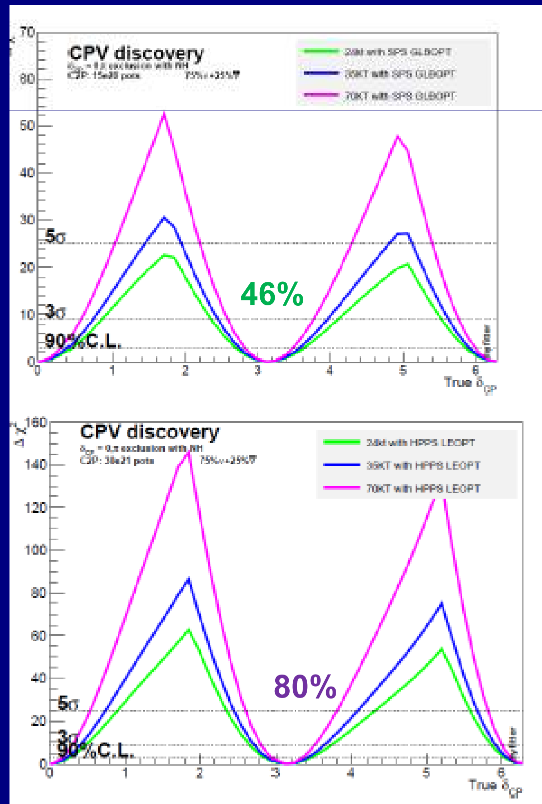
MH determination:

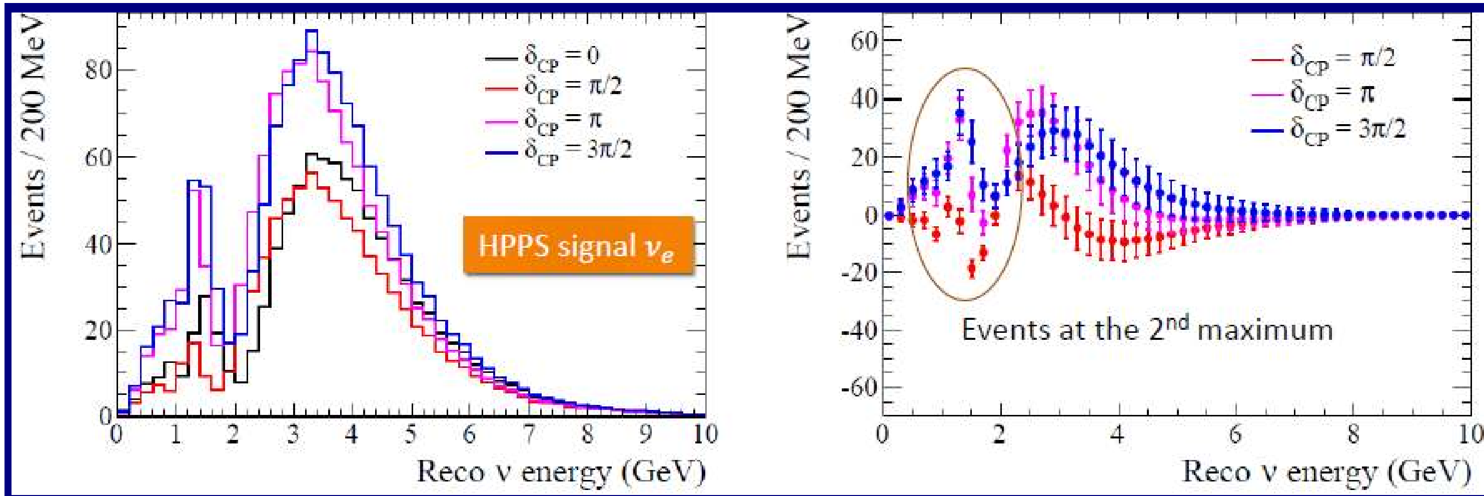
- ✓ Median 5σ C.L. (p=0.5) reached within 2 years of SPS operation at 750kW.
- ✓ Guaranteed 5σ C.L. (p=1) reached within 5 years of SPS operation at 750kW.

Beam optimization for CP violation → best CP coverage obtained for: SPS "GLB" and HPPS "LEOPT"









Rich features in the region of 2nd max

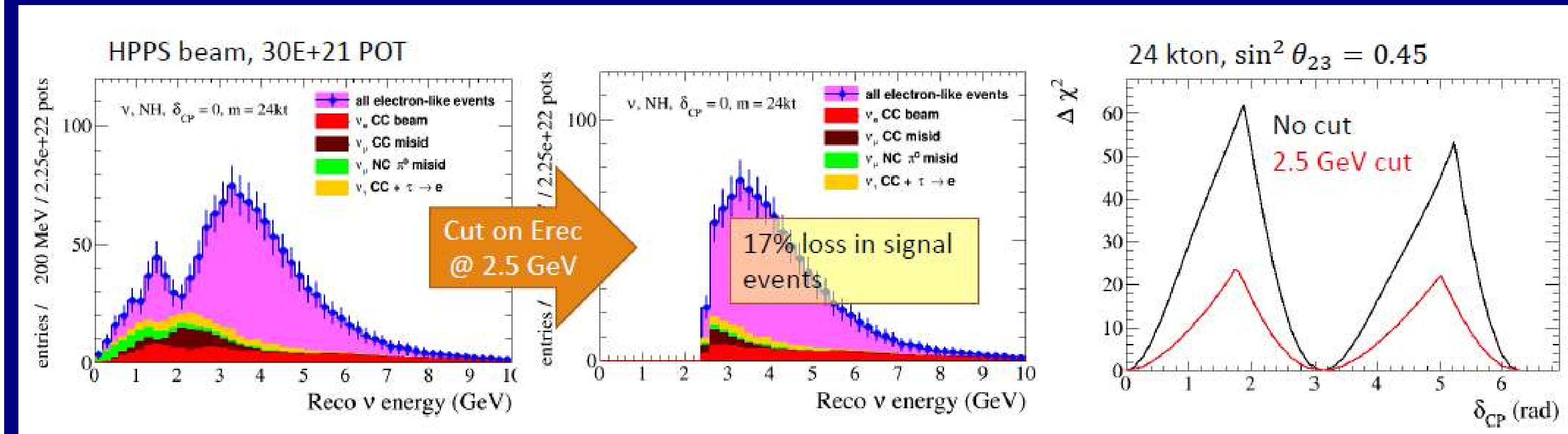
→ Less critical on normalization syst for 1st max

Illustrative example: cut at 2.5 GeV removes 17% (5%) of events for the HPPS (SPS) beam with a dramatic loss of sensitivity:

Parameter	Value	Error
Signal normalization (f_{sig})	1	3 %
Beam electron contamination normalization ($f_{\upsilon e}$)	1	5 %
Tau normalization ($f_{\upsilon \tau}$)	1	20 %
υ NC and υμ CC background (f_{NC})	1	10 %

Median coverage

	$F_{3\sigma}$	$F_{5\sigma}$
24 kton	69% → 41%	43% → 0%

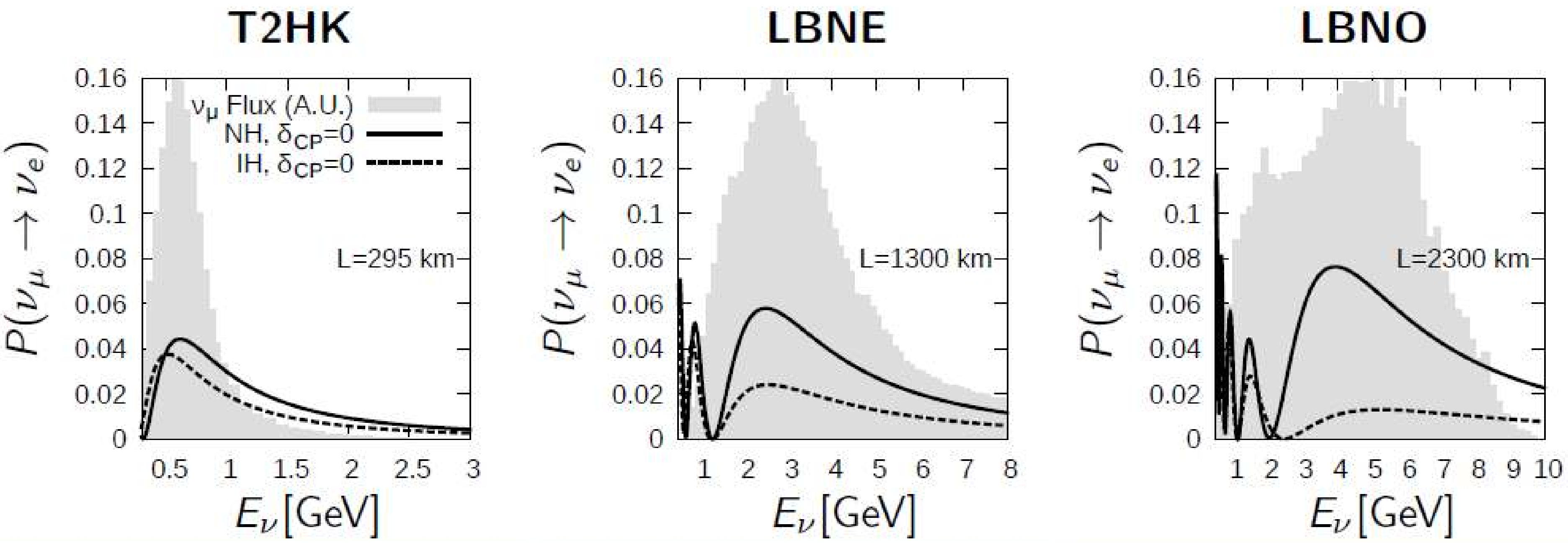


ν_e Appearance: Mass Hierarchy

M. Bass

$$P_{\nu_\mu \to \nu_e} \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2((1-x)\Delta)}{(1-x)^2}$$
$$- \alpha \sin 2\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin((1-x)\Delta)}{(1-x)}$$
$$+ \alpha \sin 2\theta_{13} \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin((1-x)\Delta)}{(1-x)}$$
$$+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

$$x = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$
$$\Delta = \frac{\Delta m^2_{31} L}{4E}$$
$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$



ν_e Appearance: CP Violation

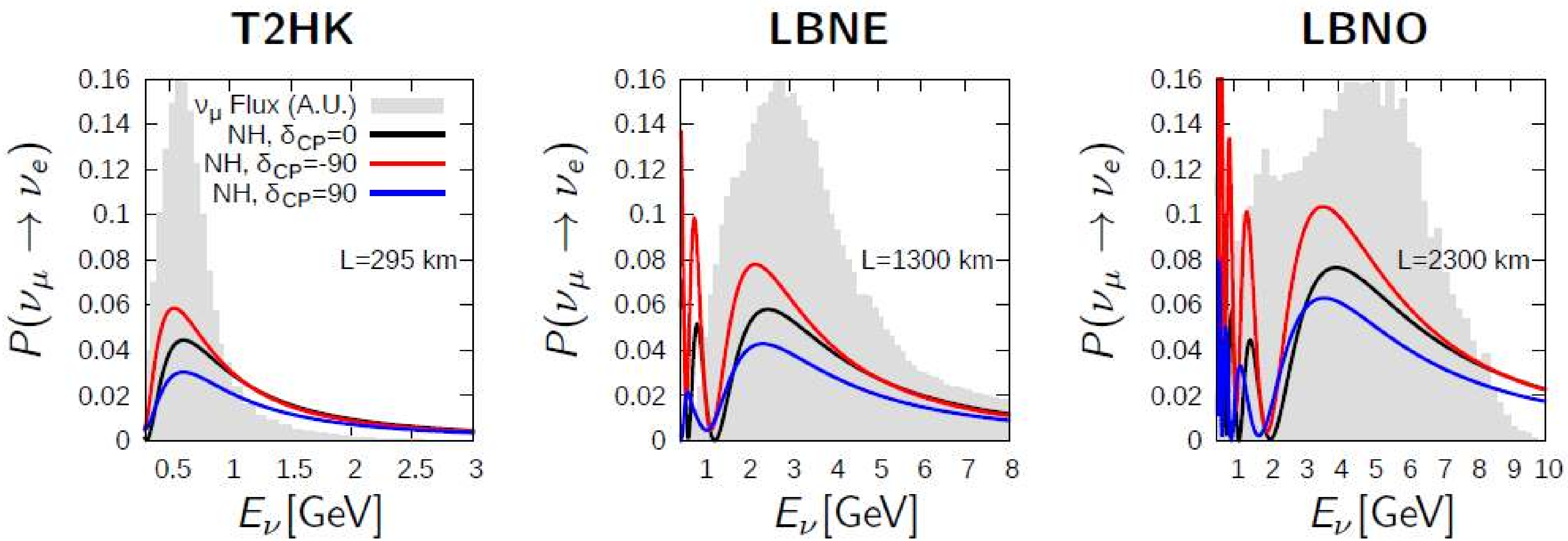
M. Bass

$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} \quad \approx \quad & \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2((1-x)\Delta)}{(1-x)^2} \\
- \quad & \alpha \sin 2\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin((1-x)\Delta)}{(1-x)} \\
+ \quad & \alpha \sin 2\theta_{13} \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin((1-x)\Delta)}{(1-x)} \\
+ \quad & \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}
\end{aligned}
$$

$$x = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$

$$\Delta = \frac{\Delta m^2_{31} L}{4E}$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$



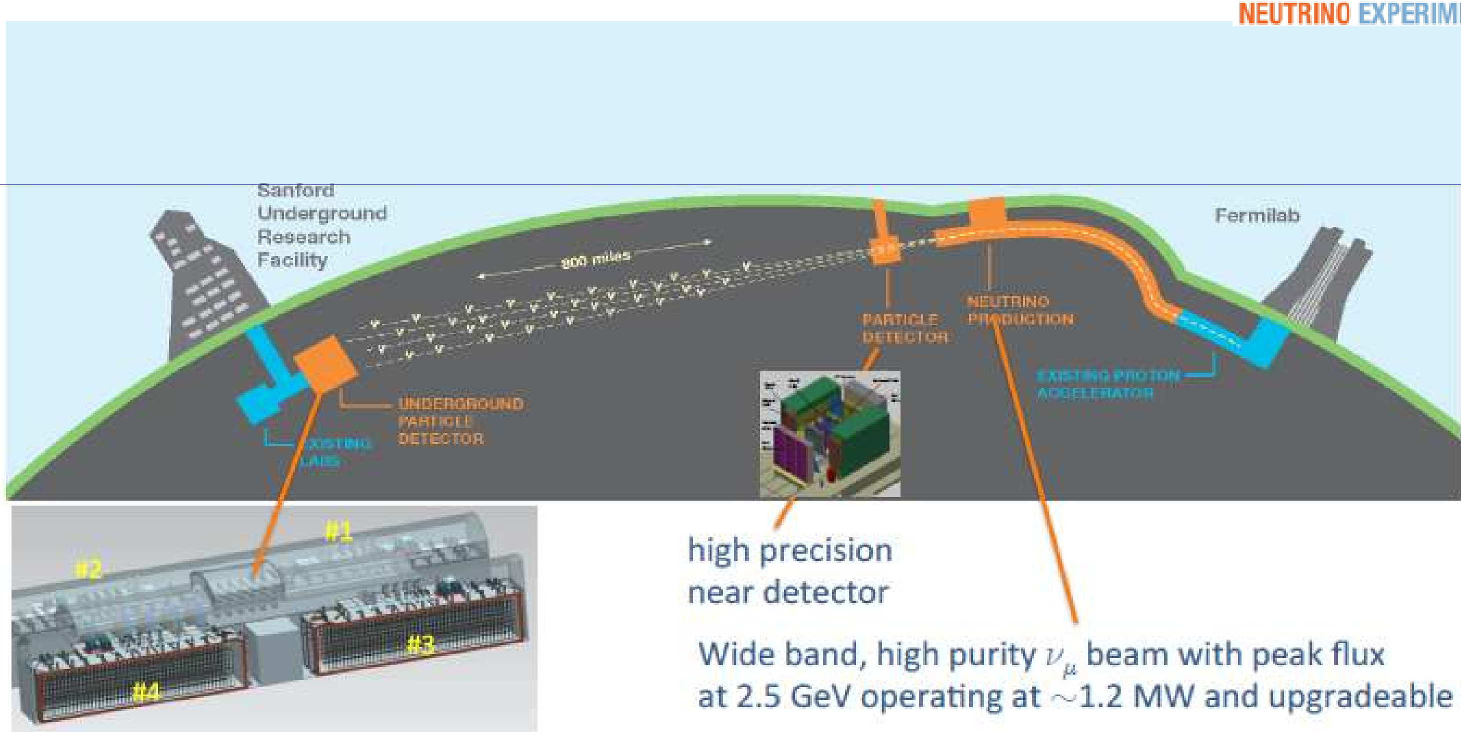
Merging on LBNO and LBNE in an international LBL program hosted in the USA based on the "LHC model"

- 40 kton LAr target at 1300 km from FNAL at the Homestake mine (LBNO experience on double-phase to achieve large mass), high precision near detector
- 1.2 MW (upgradeable to 2.4 MW) and neutrino beam with second max optimization à la LBNO

→ Start of beam operations expected in 2026

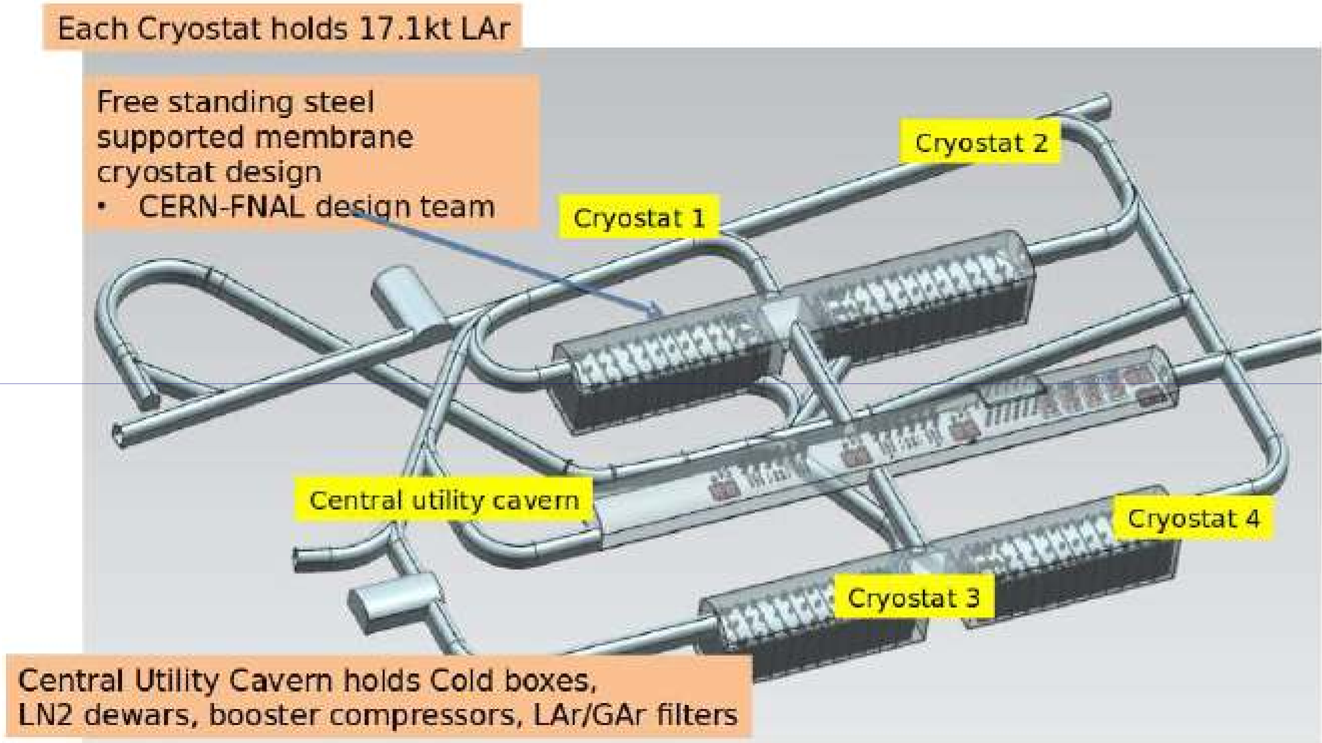
Overall Experimental Layout

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT



- four identical cryostats deep underground
- staged approach to four independent 10 kt LAr detector modules
- Single-phase and double-phase readout under consideration

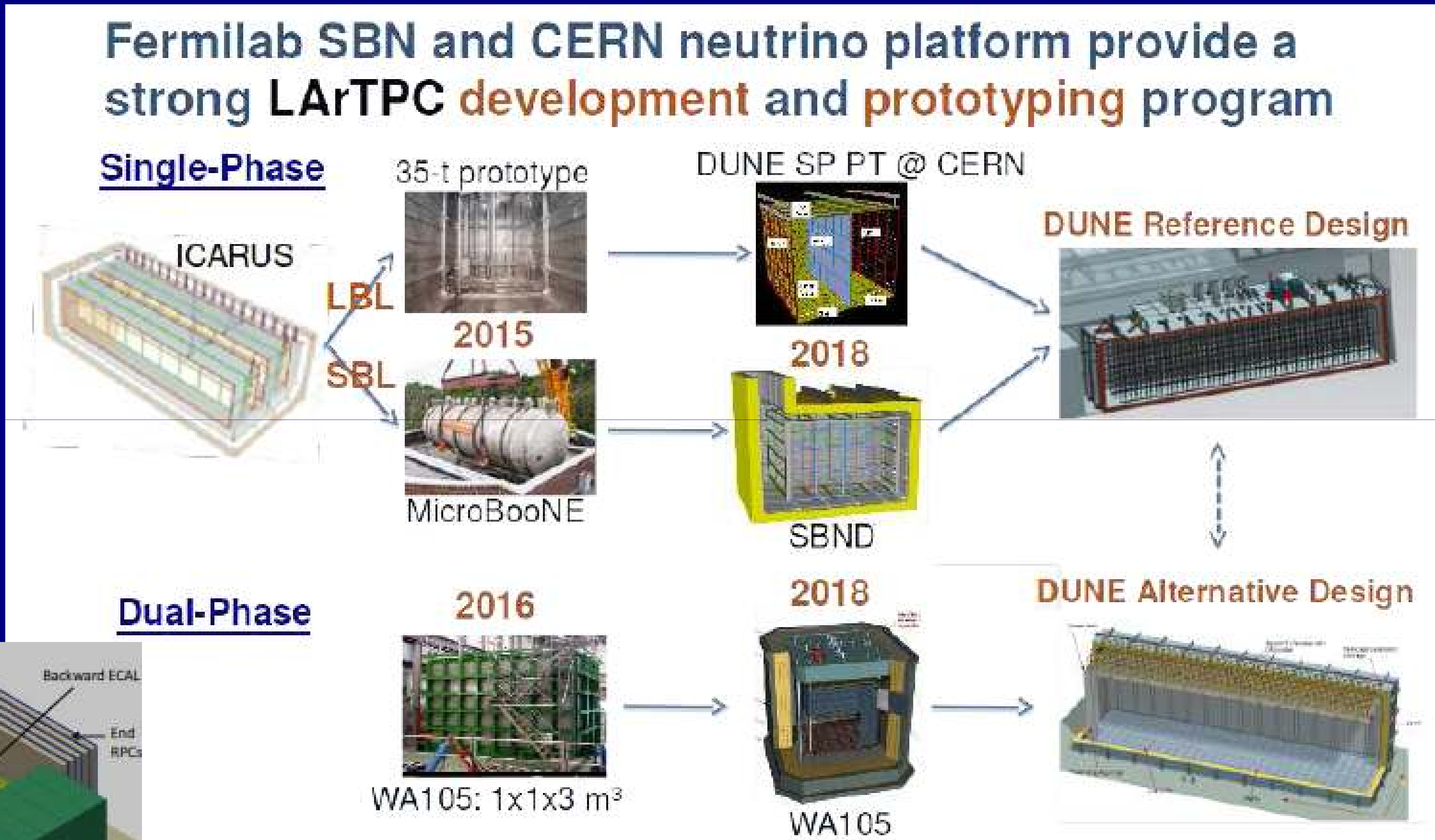
DUNE 40-kton Far Detector Underground Layout

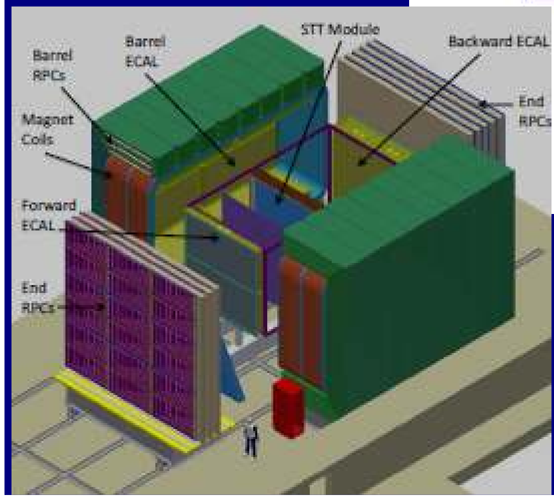


Approval of final underground cavern design (CD3a) late 2015/early 2016. Excavation starts in 2017.

A large R&D and engineering supporting program, the first 10 kton module has to start installation on a very tight schedule on 2021 and it will be in single-phase.

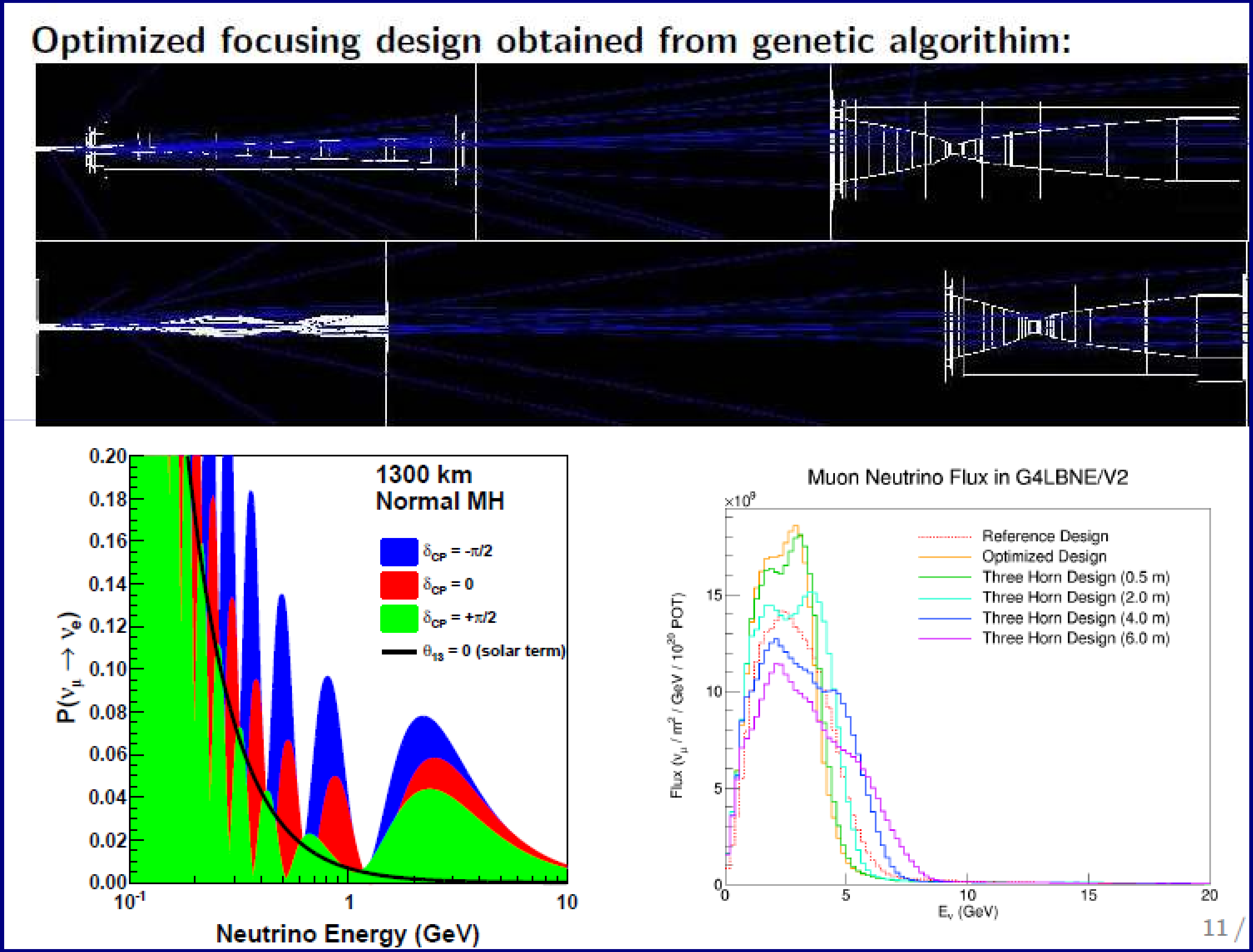
Double-phase technology important to support the achievement of 40 kton mass

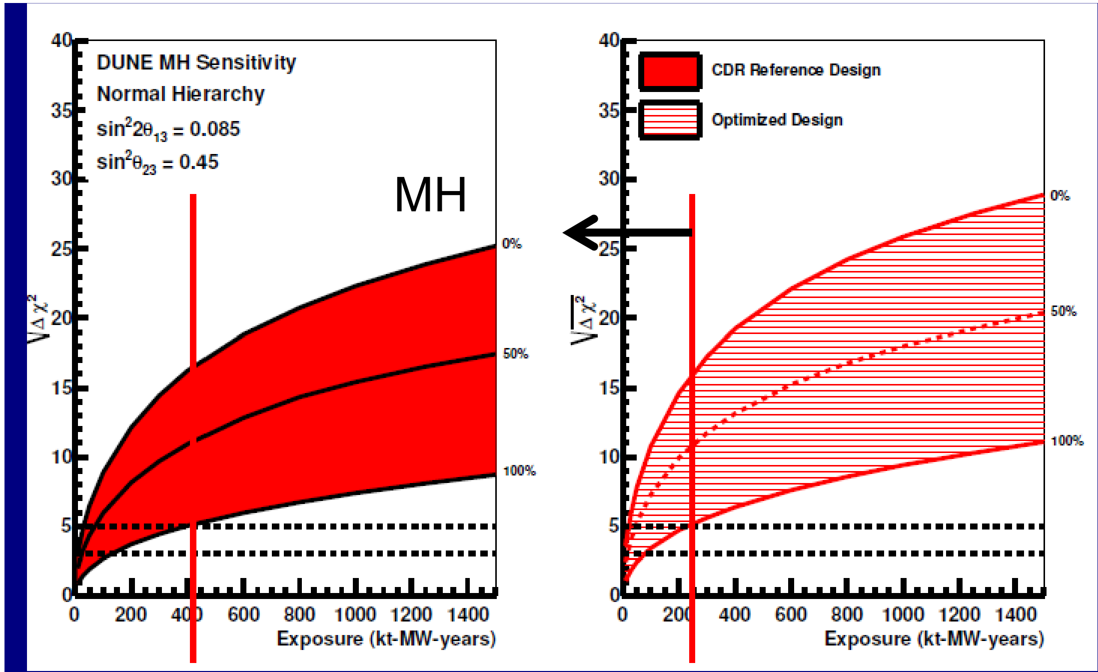




NOMAD-like near detector, control of systematics, high precision neutrino physics measurements 0(100 M) neutrino interactions

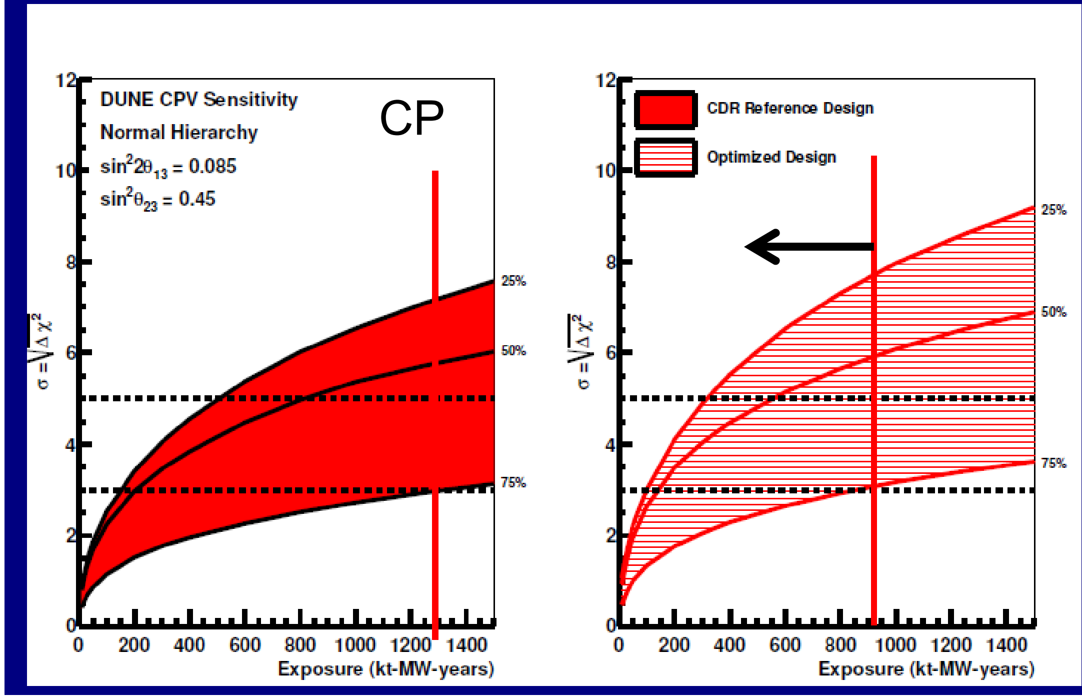
Optiimized beam focusing design based on a genetic algorithm à la LBNO to define the all parameters of the horns geometry





Reference beam

Optimised beam



Effect of beam optimization: exposure time to reach a certain significance

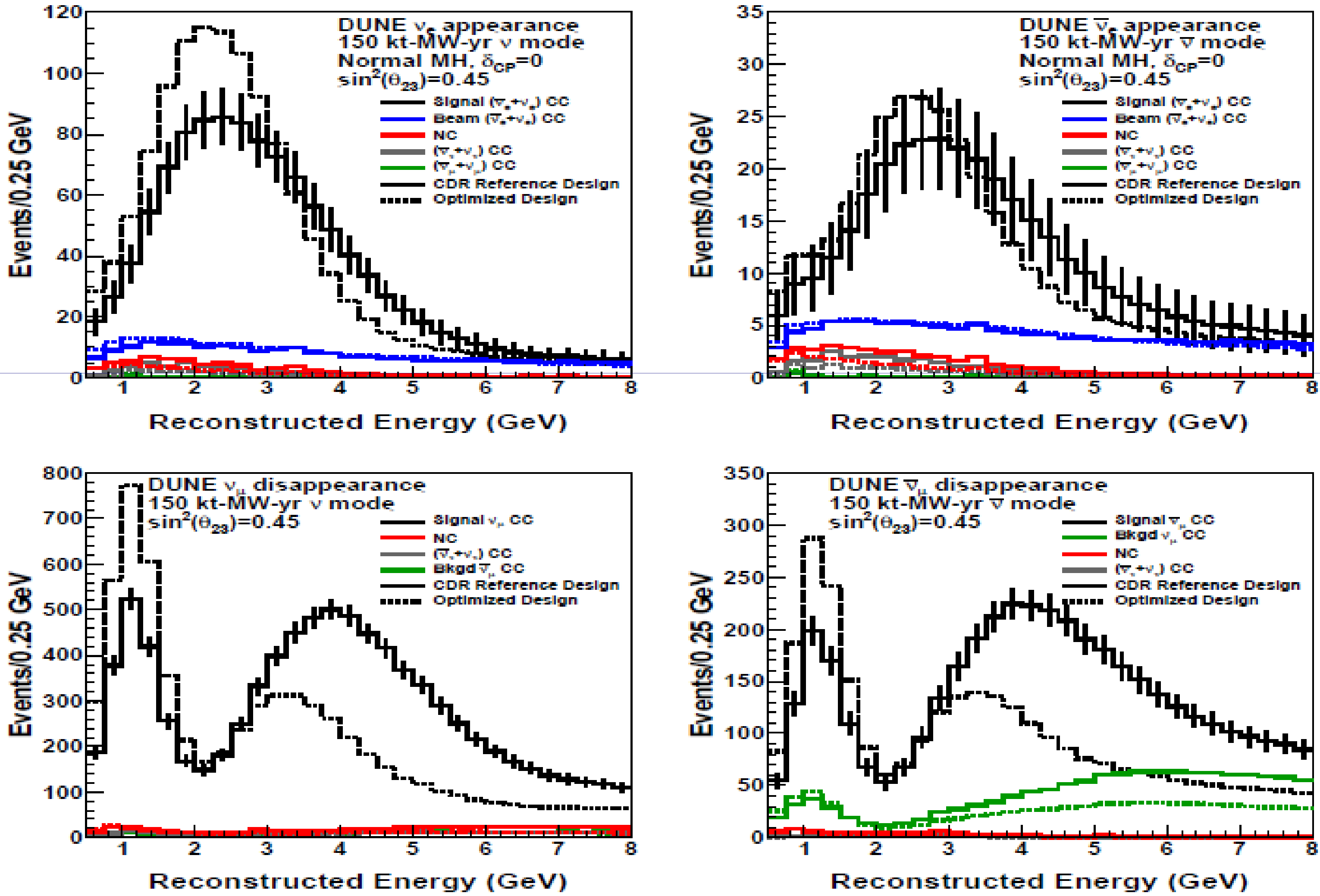
Bands for different values of:

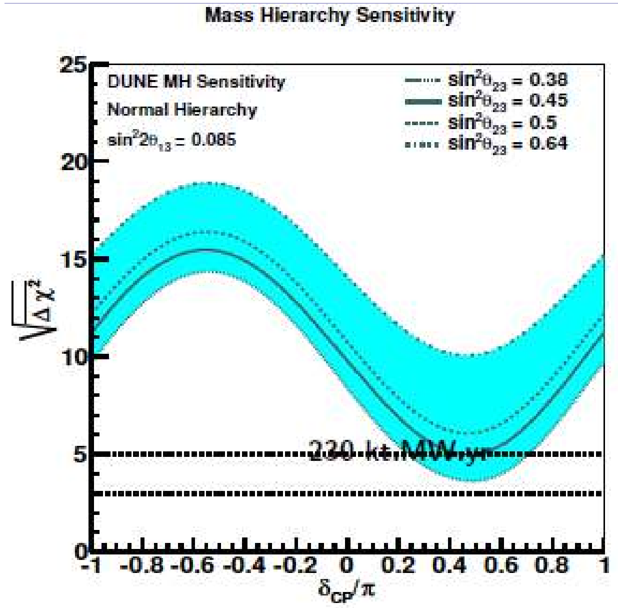
- MH probability to reach a certain significance
- Fraction of CP coverage

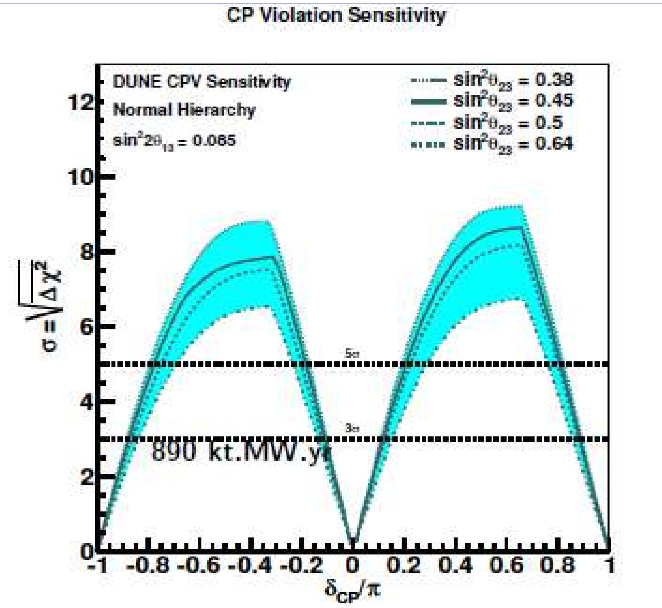
→ Optimisation process being further pursued in DUNE

Oscillation signals

Exposure: 150 kT.MW.yr (equal $\nu/\bar{\nu}$) 1MW.yr = 1×10^{21} p.o.t at 120 GeV. ($\sin^2 2\theta_{13} = 0.084,\ \sin^2\theta_{23} = 0.45,\ \delta m^2_{31} = 2.47 \times 10^{-3}$ eV^2)





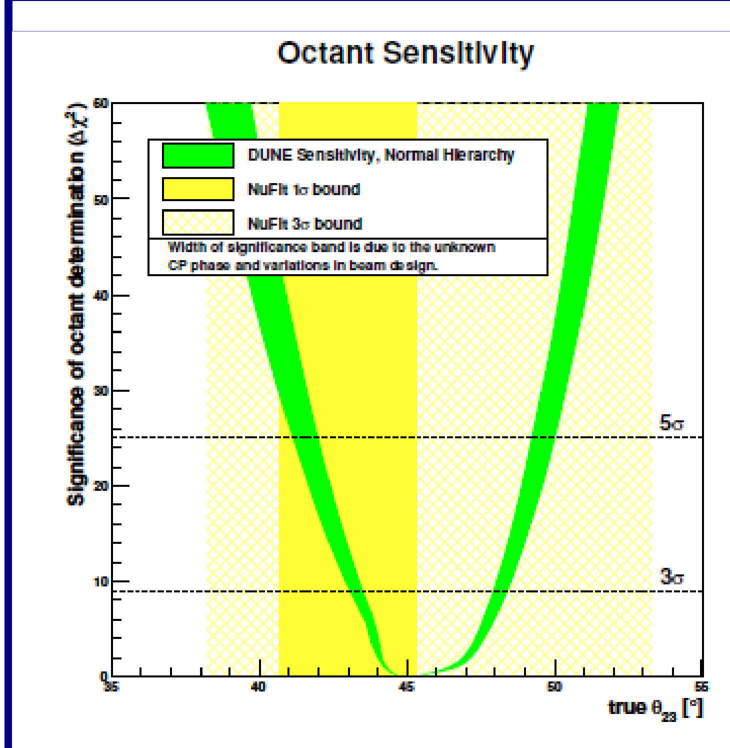


CP sensitivity:
> 3 (5) σ for 75% (50%) of delta values

CP coverage at 50%:
810 kton*MW*yr (reference beam) → 8.4 years with 40 kton at 2.4 MW

550 kton*MW*yr exposure (optimised beam) → 5.7 years with 40 kton at 2.4 MW

Sensitivity on octant definition



Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3σ ($\delta_{CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{CP} = 0$)	450	290
CPV at 5σ ($\delta_{CP} = -\pi/2$)	525	320
CPV at 5σ 50% of δ_{CP}	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of δ_{CP}	1320	850

Conclusions:

- The study of neutrinos provides fundamental information in particle physics, astrophysics and cosmology. They are a window on the physics beyond the SM. Unfortunately there are a lot of things I did not have time to mention in this lecture

- Experimental neutrino physics is a challenging field with a large variety of techniques requiring a lot of imagination at the level of the detectors and neutrino sources

- The history since the start of the Davis experiment in 1968 has shown many surprises. New ones may still be possible and there are still anomalies and aspects to be clarified

- The study of CP violation in the neutrino sector is now accessible and it is at the core of an unprecedented international effort among Europe and USA

- A last « anthropic-like » consideration ;-)

Although neutrino measurements are not easy Nature has been kind to us so far: somehow we have been lucky that the Δm^2 among the 3 mass states are such that the related solar and atmospheric oscillations are accessible with experimental means on earth ! We have been lucky that the large mixing angle solution is the one for solar neutrinos and again that θ_{13} is large and just below the CHOOZ limit.
Maybe this will happen again with CP violation ….