The on-going

programme

3-family oscillation matrix (Pontecorvo, Maki, Nakagawa, Sakata)

S = sine c = cosine

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

- δ CP violation phase.
- θ_{12} drives SOLAR oscillations: $\sin^2\theta_{12} = 0.32^{+0.05}_{-0.04}$ (+- 16%)
-
- θ_{23} drives ATMOSPHERIC oscillations: $\sin^2\theta_{23} = 0.50^{+0.13}_{-0.12}$ (+-18%)
-
- θ_{13} the MISSING link ! $\sin^2\theta_{13} < 0.033$ Set by a reactor experiment: CHOOZ.

Present status of the mixing matrix

$$U_{CKM} \dashrightarrow \begin{bmatrix} 1.0 & 0.2 & 0.001 \\ 0.2 & 1.0 & 0.01 \\ 0.001 & 0.01 & 1.0 \end{bmatrix}$$

$$U_{MNS} \dashrightarrow \begin{bmatrix} 0.8 & 0.5 & <0.3 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{bmatrix}$$

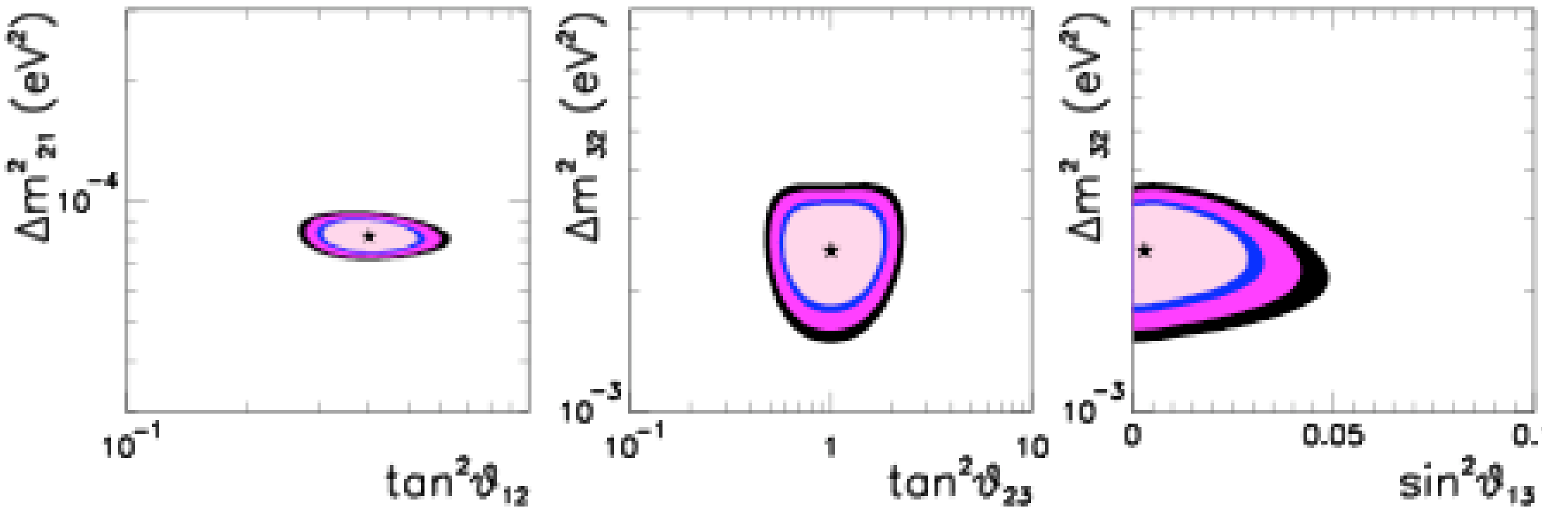
The quark mixing matrix

- is mostly diagonal
- Has a definite hierarchy
- Is Symmetrical

Why is the neutrino matrix so different?

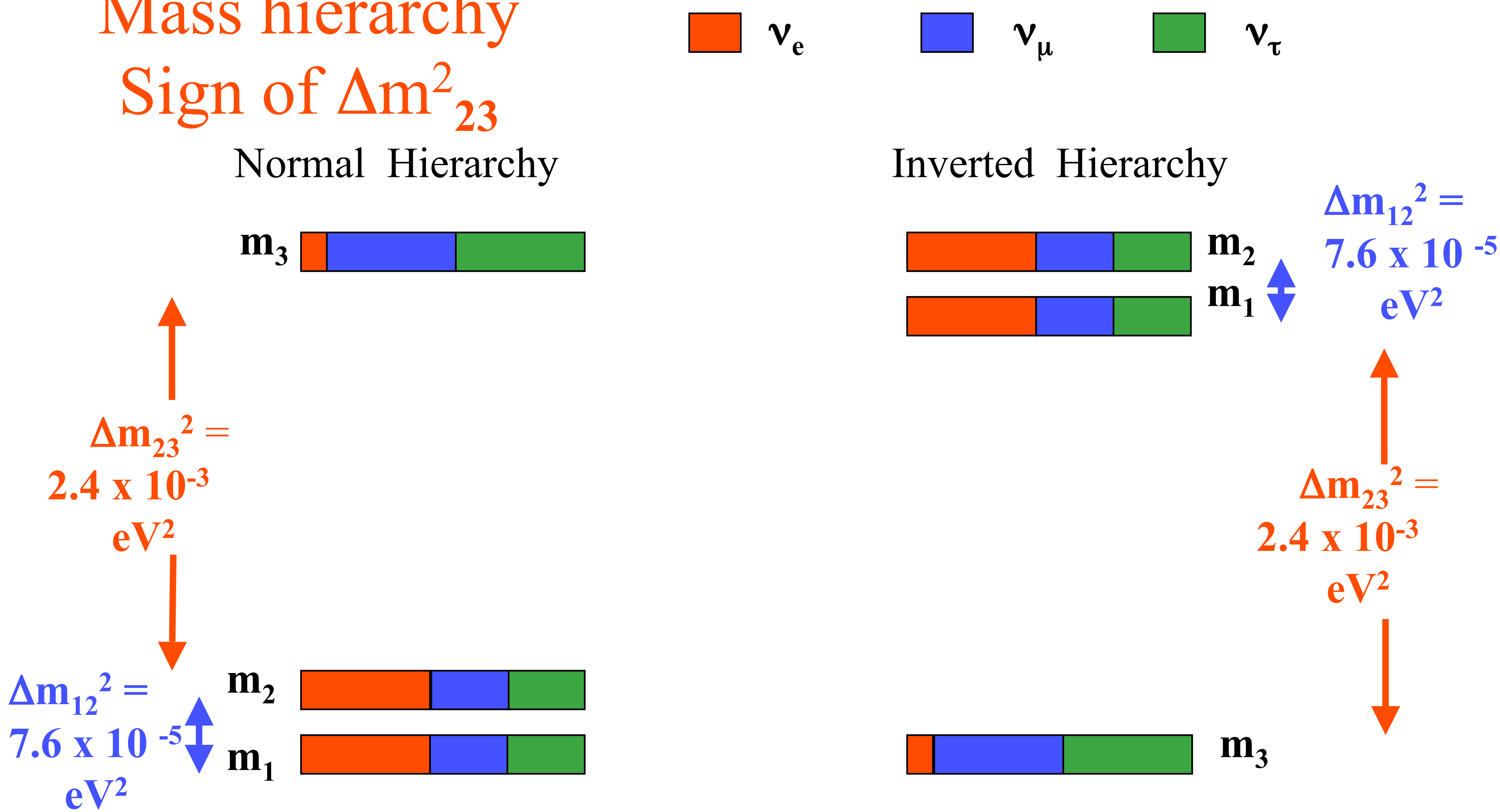
- Terms are of the same order
- Except for one
- No definite hierarchy

Angles and their meanings



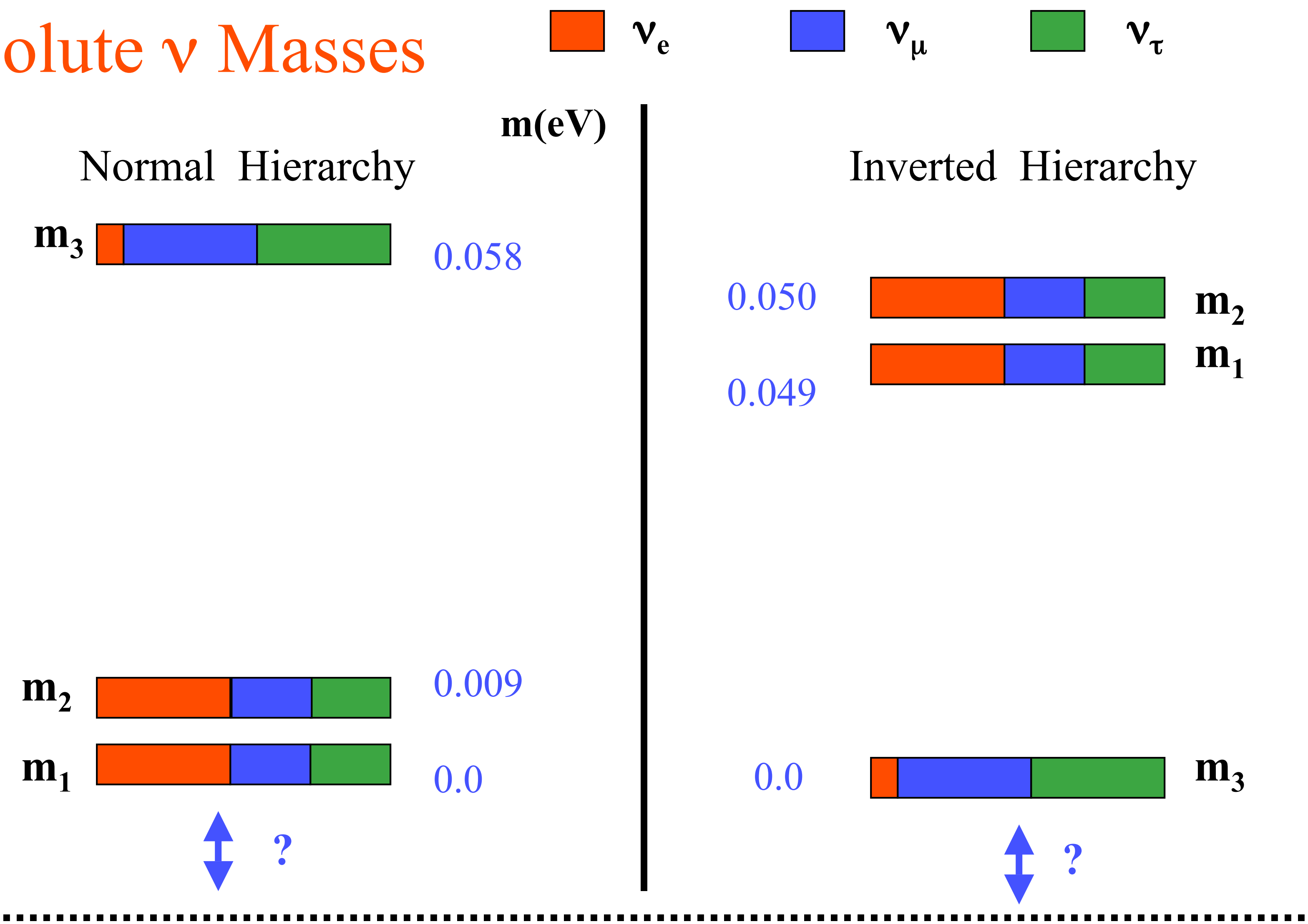
- $\sin^2 \theta_{13}$: amount of ν_e in ν_3
- $\tan^2 \theta_{12}$ Ratio of ν_e in ν_2 to ν_e in ν_1 < 1 So more in ν_1
- $\tan^2 \theta_{23}$: Ratio ν_μ to ν_τ in ν_3. If $\theta_{23}=\pi/4$ Maximal mixing equal amounts.

Mass hierarchy
Sign of Δm^2_{23}



Oscillations only tell us about DIFFERENCES in masses
Not the ABSOLUTE mass scale: Direct measurements or Double β decay

Absolute ν Masses



We DO have a LOWER LIMIT on at least one neutrino: $(2.4 \times 10^{-3})^{1/2} > 0.05$ eV

3-ν oscillation formula: ν_α ---> ν_{β}. I

$$\mathbf{P}_{\alpha\beta} = | < \nu_\beta | \nu_\alpha(\mathbf{t}) > |^2$$

$$| < \nu_\beta | \nu_\alpha(\mathbf{t}) > |^2 = |(\sum_{j=1}^{3} \mathbf{U}_{\beta j} < \nu_j|)(\sum_{i=1}^{3} \mathbf{U}^*_{\alpha i} \mathbf{e}^{-m_i^2 L/2E} | \nu_i >)|^2$$

$$= | \sum_{i=1}^{3} \mathbf{U}^*_{\alpha i} \mathbf{U}_{\beta i} \mathbf{e}^{-i m_i^2 L/2E} |^2$$

$$= (\sum_{j=1}^{3} \mathbf{U}_{\alpha j} \mathbf{U}^*_{\beta j} \mathbf{e}^{i m_j^2 L/2E})(\sum_{i=1}^{3} \mathbf{U}^*_{\alpha i} \mathbf{U}_{\beta i} \mathbf{e}^{-i m_i^2 L/2E})$$

$$\mathbf{P}_{\alpha\beta} = \delta_{\alpha\beta} - \sum_{i>j} \sum_{j=1}^{3} \mathbf{U}^*_{\alpha i} \mathbf{U}_{\beta i} \mathbf{U}_{\alpha j} \mathbf{U}^*_{\beta j} \ \sin^2 \frac{(m_i^2 - m_j^2) L}{4E}$$

3-ν oscillation formula: ν_μ ---> ν_{τ}. II

Assume $\delta_{CP} = 0$ for simplicity. $U_{ij} = U^*_{ij}$

With $\mathbf{i} > \mathbf{j}$

$$P_{\mu\tau} = -4\sum_{i>j} U_{\mu i}U_{\tau i}U_{\mu 1}U_{\tau 1}\ \sin^2\frac{(m_i^2 - m_1^2)L}{4E} \qquad (j = 1)$$

$$-4\sum_{i>j} U_{\mu i}U_{\tau i}U_{\mu 2}U_{\tau 2}\ \sin^2\frac{(m_i^2 - m_2^2)L}{4E} \qquad (j = 2)$$

$$-4\sum_{i>j} U_{\mu i}U_{\tau i}U_{\mu 3}U_{\tau 3}\ \sin^2\frac{(m_i^2 - m_3^2)L}{4E} \qquad (j = 3)$$

3-ν oscillation formula: ν_μ ---> ν_{τ}. II

With

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

$$P_{\mu\tau} = -4U_{\mu 1}U_{\tau 1}[U_{\mu 2}U_{\tau 2}\ \sin^2\frac{\Delta m^2_{21}L}{4E} + U_{\mu 3}U_{\tau 3}\ \sin^2\frac{\Delta m^2_{31}L}{4E}]$$

$$-4U_{\mu 2}U_{\tau 2}[U_{\mu 3}U_{\tau 3}\ \sin^2\frac{\Delta m^2_{32}L}{4E}]$$

The solar term is quite small

For atmospheric neutrino parameters

$$\frac{\Delta m^2_{21}L}{4E} = 1.27\frac{7.9\text{x}10^{-5}1000\text{km}}{4\text{x}1\text{GeV}} = 0.025$$

After squaring, we can neglect it

Since Δm^2_{21}(solar) << Δm^2_{32} or Δm^2_{31}(atmos)

We can also set

7.9×10^{-5} << 2.4×10^{-3}

$$\Delta m^2_{31} = \Delta m^2_{32}$$

Why we can treat oscillations as a 2 ν phenomenon sometimes.

$$P_{\mu\tau} = -4U_{\mu 3}U_{\tau 3}[U_{\mu 1}U_{\tau 1} + U_{\mu 2}U_{\tau 2}]\ \sin^2\frac{\Delta m^2_{32}L}{4E}$$

Using a Unitarity relation:

$$U_{\mu 1}U_{\tau 1} + U_{\mu 2}U_{\tau 2} + U_{\mu 3}U_{\tau 3} = 0$$

$$P_{\mu\tau} = 4(U_{\mu 3}U_{\tau 3})^2\ \sin^2\frac{\Delta m^2_{32}L}{4E}$$

$$= 4(s_{23}c_{13}.c_{23}c_{13})^2\ \sin^2\frac{\Delta m^2_{32}L}{4E}$$

$$= (2s_{23}c_{23})^2 c^2_{13}\ \sin^2\frac{\Delta m^2_{32}L}{4E}$$

$$= \sin^2 2\theta_{23}\ c^2_{13}\ \sin^2\frac{\Delta m^2_{32}L}{4E}$$

and $c_{13} \sim 1.0$

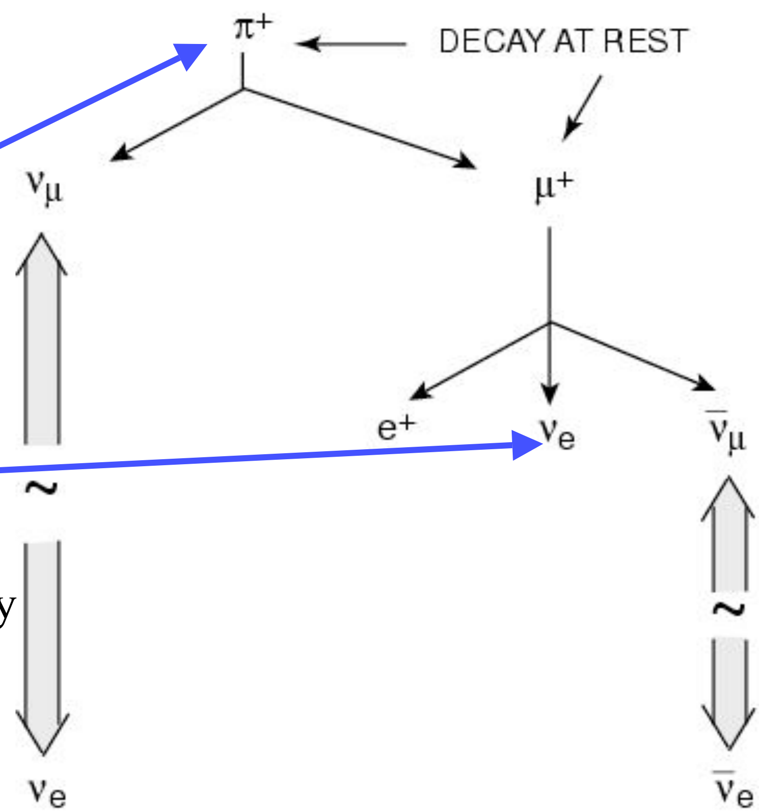
Same formula as starting with 2 neutrinos only

Every observation fits this scenario

EXCEPT…….

LSND

- 800 MeV protons in a dump.
- Positive Pions and then muons coming to rest
- and then decaying
- Look for $\overline{\nu}_\mu$ to $\overline{\nu}_e$ oscillations
- Through the reaction: $\overline{\nu}_e + p \rightarrow e^+ + n$
- Observe e^+ + photons from neutron capture in the scintillator
- Delayed coincidence
- Why not $\overline{\nu}_e$ from $\pi^- \rightarrow \mu^- \rightarrow \overline{\nu}_e$ decay chain ?
  - π^-/π^+ production 1/8
  - π- coming to rest in dump captured before decay
  - Only decays in flight contribute 1/20
  - Most μ^- captured before decay 1/8
- Overall reduction **7.5 x 10 $^{-4}$**.

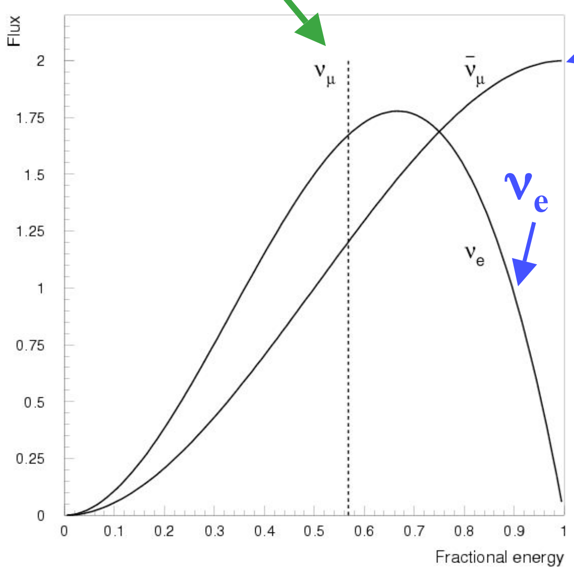


LSND spectrum and detector

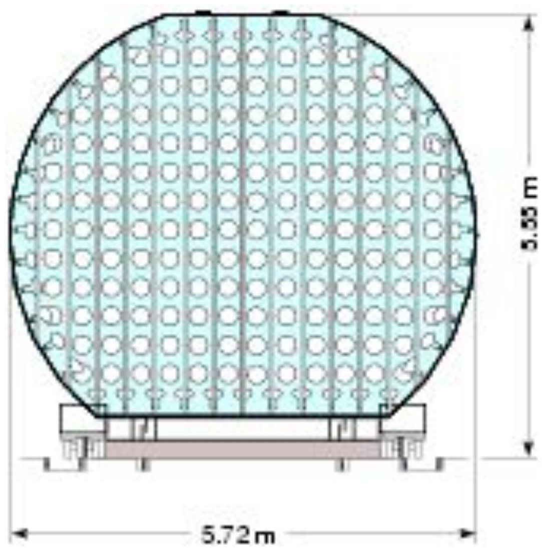
ν_μ from π decay

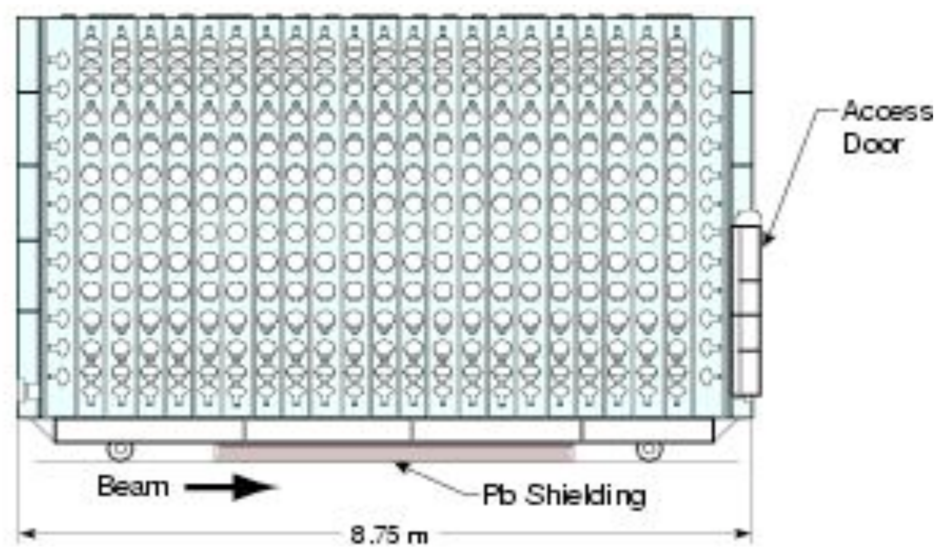
$\bar{\nu}_\mu$ from μ decay: look for oscillations of these to $\bar{\nu}_e$

ν_e from μ decay



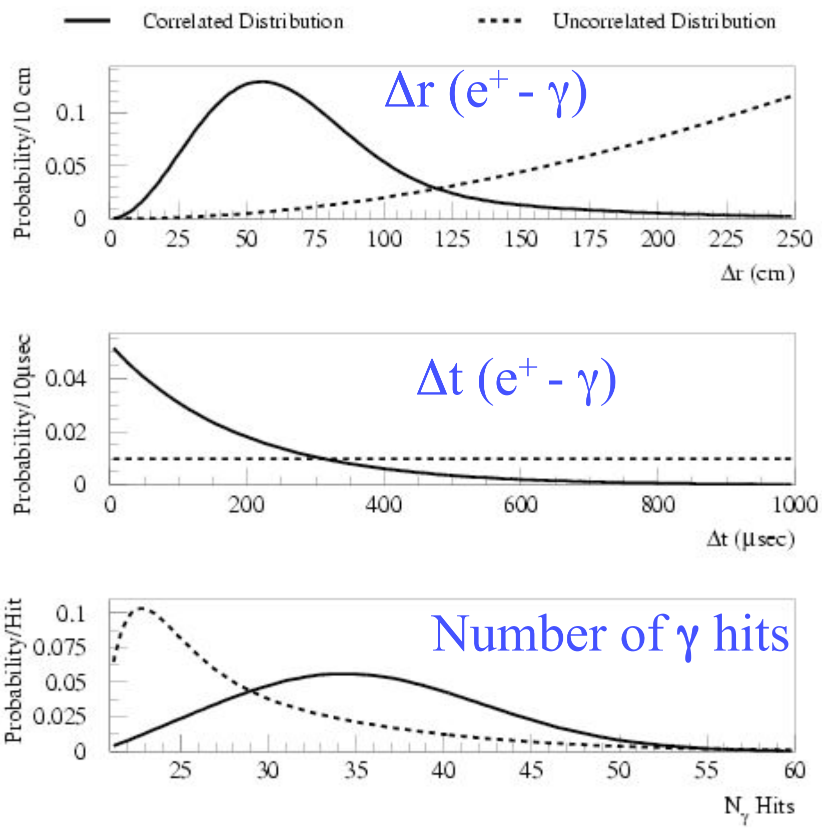
- 30m from dump
- 167 tons of liquid scintillator
- 1220 pmt + 292 veto
- Cerenkov + scintillator light



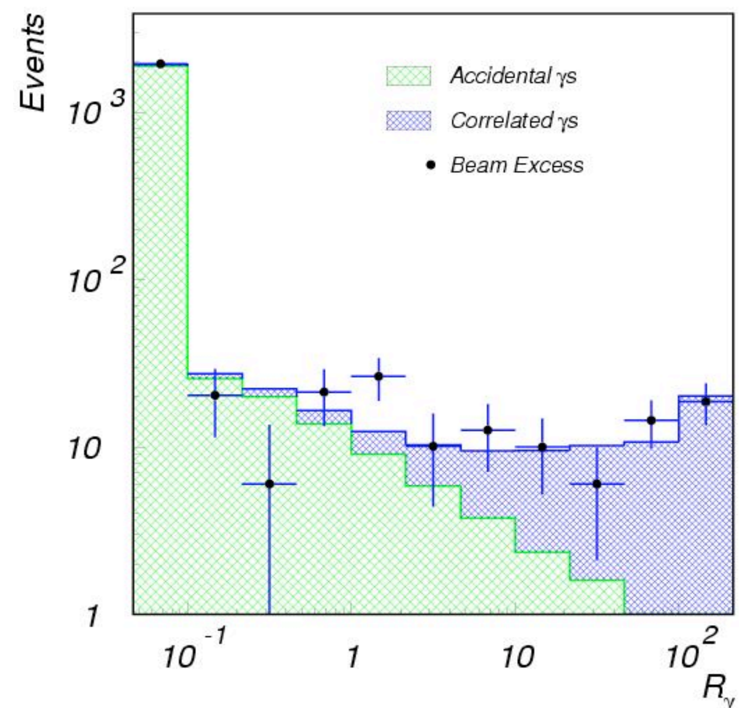


Discriminating variables: Likelihood

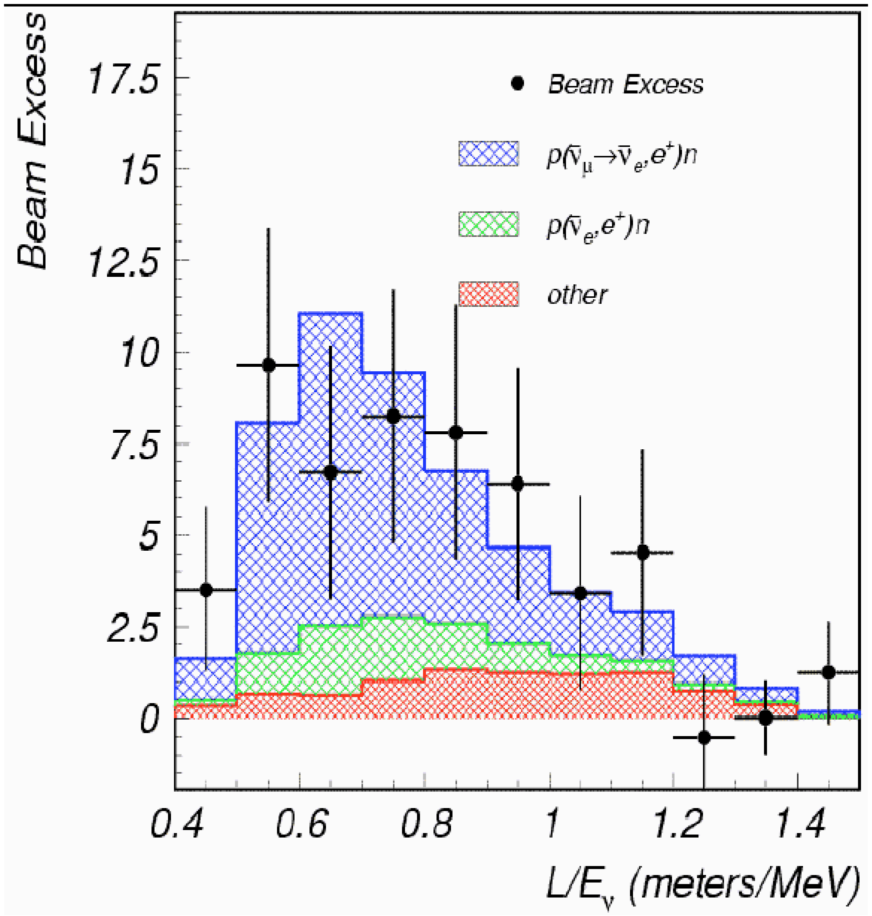
$\nu_e + p \rightarrow e^+ + n$ → Captured giving photon



Likelihood ratio



LSND result



Excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam,

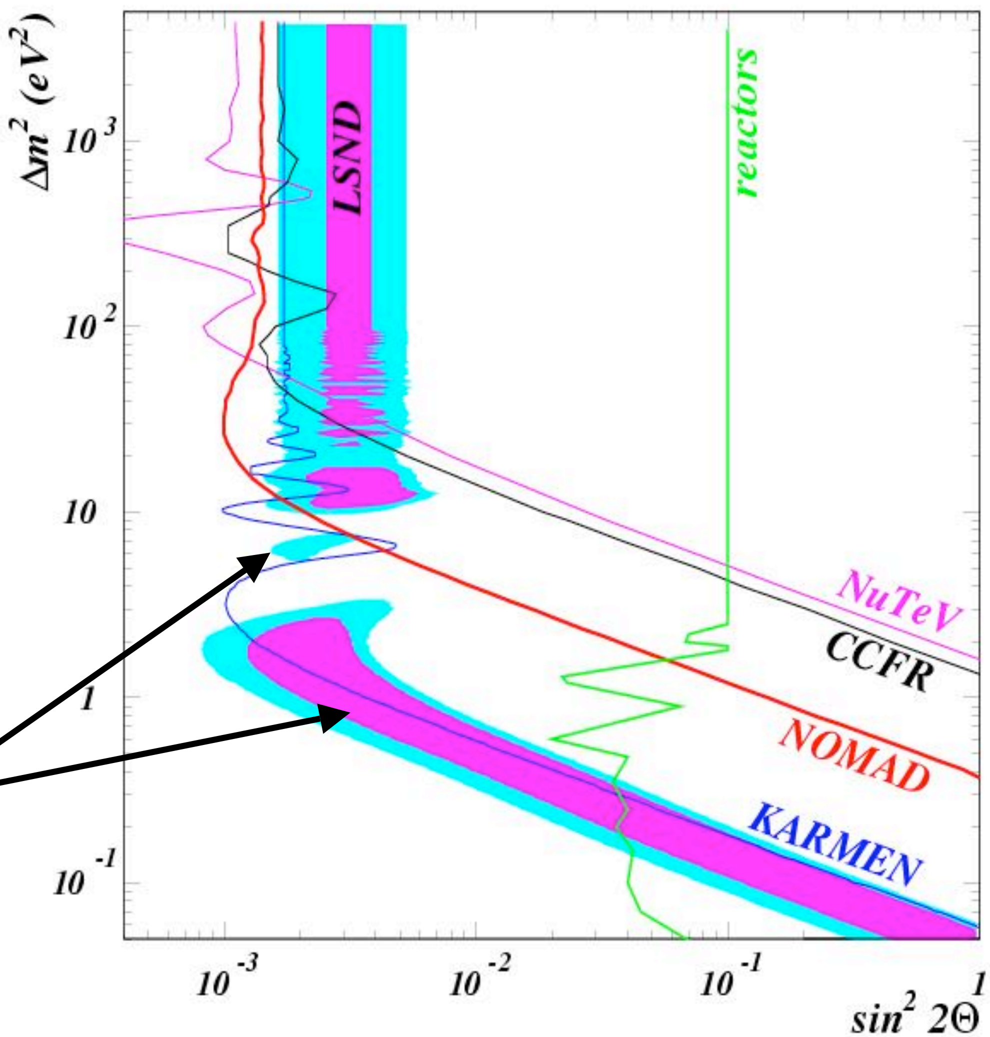
87.9 ± 22.4 ± 6.0 (3.8σ)

which can be interpreted as $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

0.26% oscillation probability.

L/E ~ 1

Exclusion by other experiments



Some areas left unchecked at low Δm^2

Notice the **LARGE Δm^2 .**

Incompatible with Either atmospheric Or solar Δm^2.

Why is this important?

- The mass region does NOT fit with any of the other two.
- Three mass differences imply that there should be at

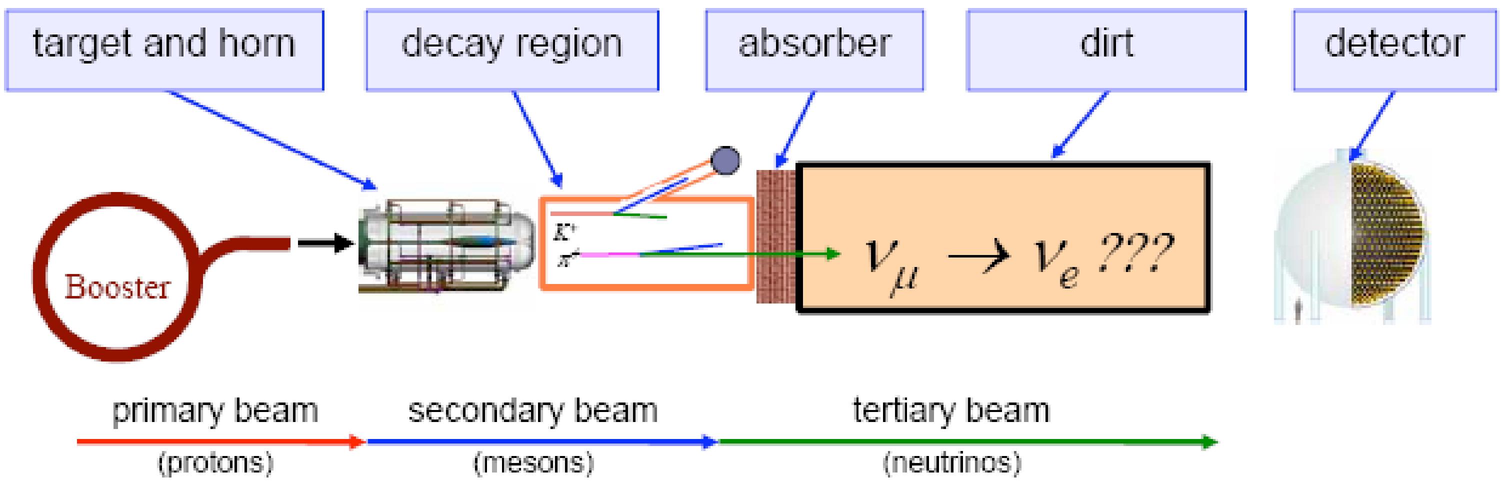
  least one more neutrino.
- But LEP measured just **2.994 ± 0.012** neutrino types from Z^0 width.
- $\Gamma_{inv} = \Gamma_{tot} - \Gamma_{vis} = 498$ MeV
- $\Gamma_{\nu\nu} = 165$ MeV ---> $N_\nu \sim 3$
- So it means that this potential extra neutrino

  DOES NOT couple to the Z^0.
- It must be **STERILE**.
- Must be checked.

MiniBooNE

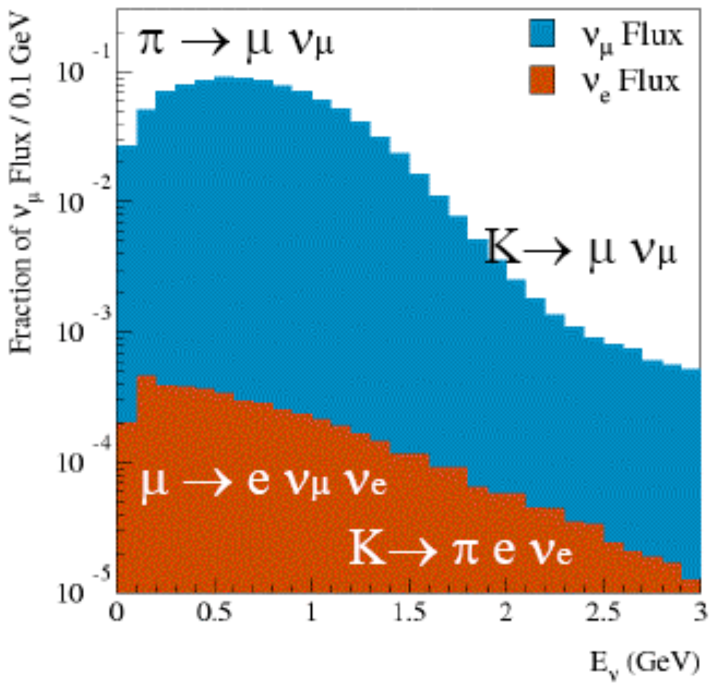
- Keep same L/E as LSND ~ 1.0 → 500m and 500 MeV
- Look for ν_e appearance in ν_μ beam

  (assuming CP invariance same as $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam.)
- T



The MiniBooNE neutrino beam spectrum from the Fermilab 8 GeV booster

Neutrino Flux from GEANT4 Simulation



$\nu_e/\nu_\mu = 0.5\%$
Antineutrino content: 6%

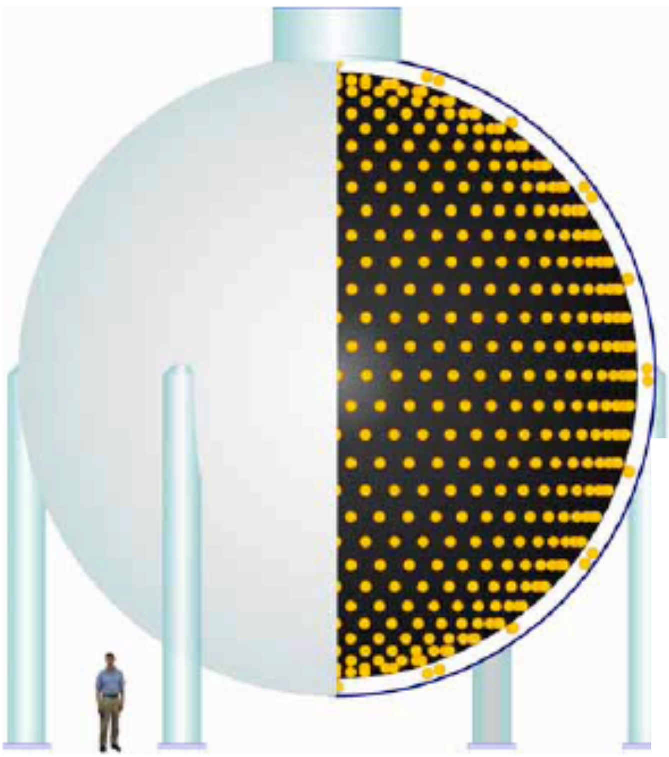
"Intrinsic" $\nu_e + \bar{\nu}_e$ sources:

$\mu^+ \rightarrow e^+\ \bar{\nu}_\mu\ \nu_e$ (52%)
$K^+ \rightarrow \pi^0\ e^+\ \nu_e$ (29%)
$K^0 \rightarrow \pi\ e\ \nu_e$ (14%)
Other (5%)

Irreducible background

Accumulated:
5 x 10^{20} Protons on target

The MiniBooNE Detector



- 541 meters downstream of target
- 3 meter overburden
- 12 meter diameter sphere

  (10 meter "fiducial" volume)

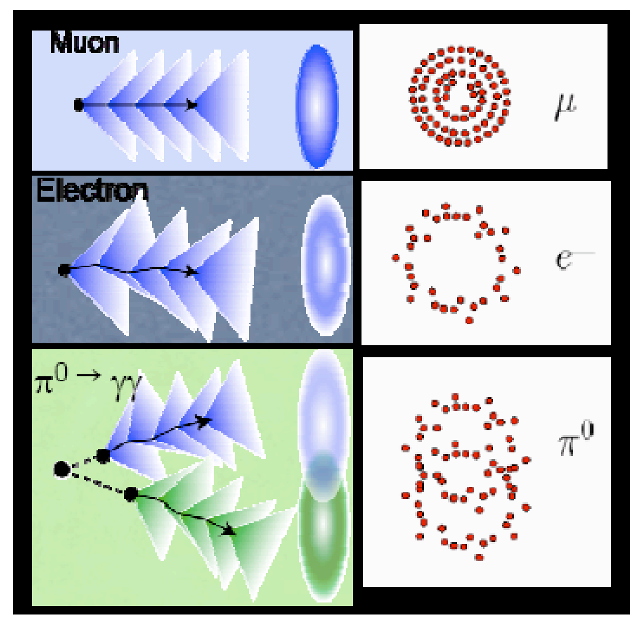
  - Filled with 800 tons

    of pure mineral oil (CH_2)

Muons:
Produced in most CC events.
Usually 2 subevent or exiting.

Electrons:
Tag for $\nu_\mu \rightarrow \nu_e$ CCQE signal.
1 subevent

NCπ^0s:
Can form a background if one photon is weak or exits tank.
In NC case, 1 subevent.

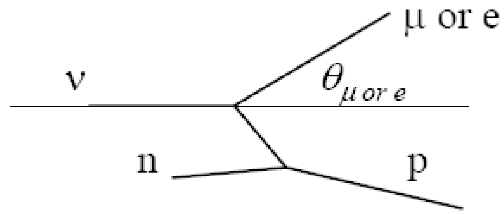


Neutrino interactions

Focus on quasi-elastic interactions

CCQE $\nu_\mu + n \rightarrow \mu^- + p$
(Charged Current Quasi-Elastic)

39% of total



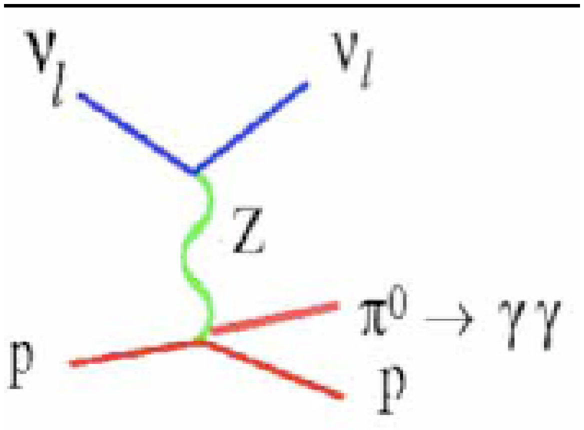
$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)}\cos\theta_\ell}$$

Reconstructed from:
Scattering angle
Visible energy ($E_{visible}$)

To claim any effect must:

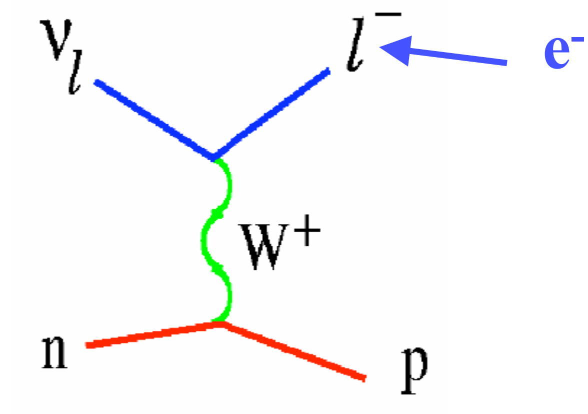
- Understand neutrino cross sections: especially difficult at low energy due to Fermi motion, nuclear reinteractions, Pauli blocking,….
- Intrinsic ν_e in the beam

Backgrounds



π^0 from NC

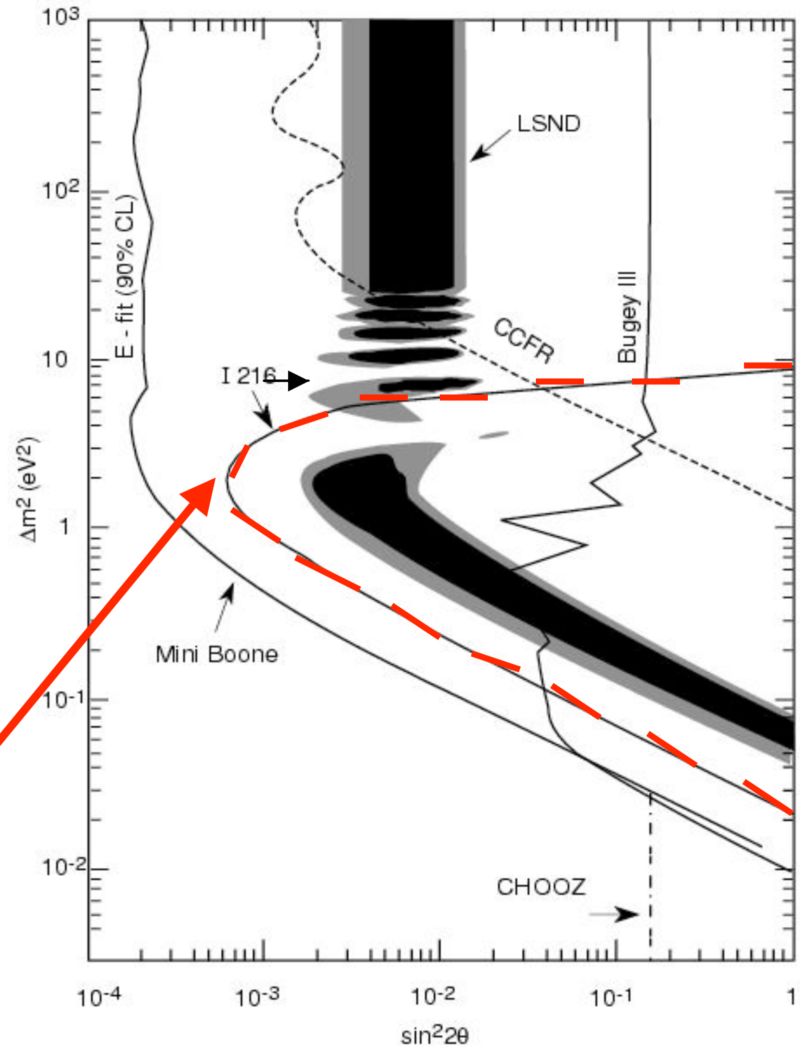
99% recognized as two showers



Intrinsic ν_e in the beam

I216

- CERN experiment to check LSND
- ν_e appearance in a ν_μ beam.
- Difference from MinBooNE:
- Use a NEAR detector to know precisely the intrinsic ν_e content of the beam.
- Compare spectra at NEAR and FAR detectors.
- Sensitivity
- Experiment was NOT approved.

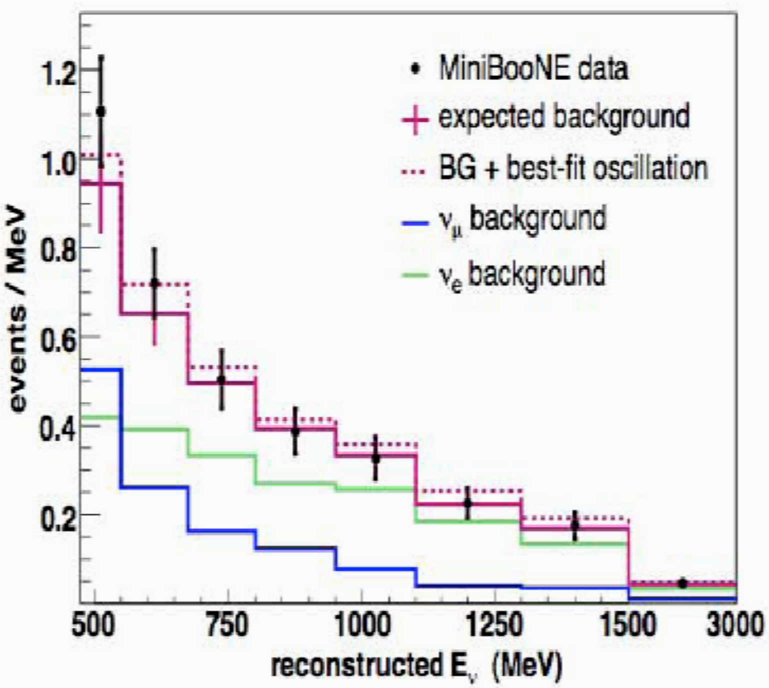


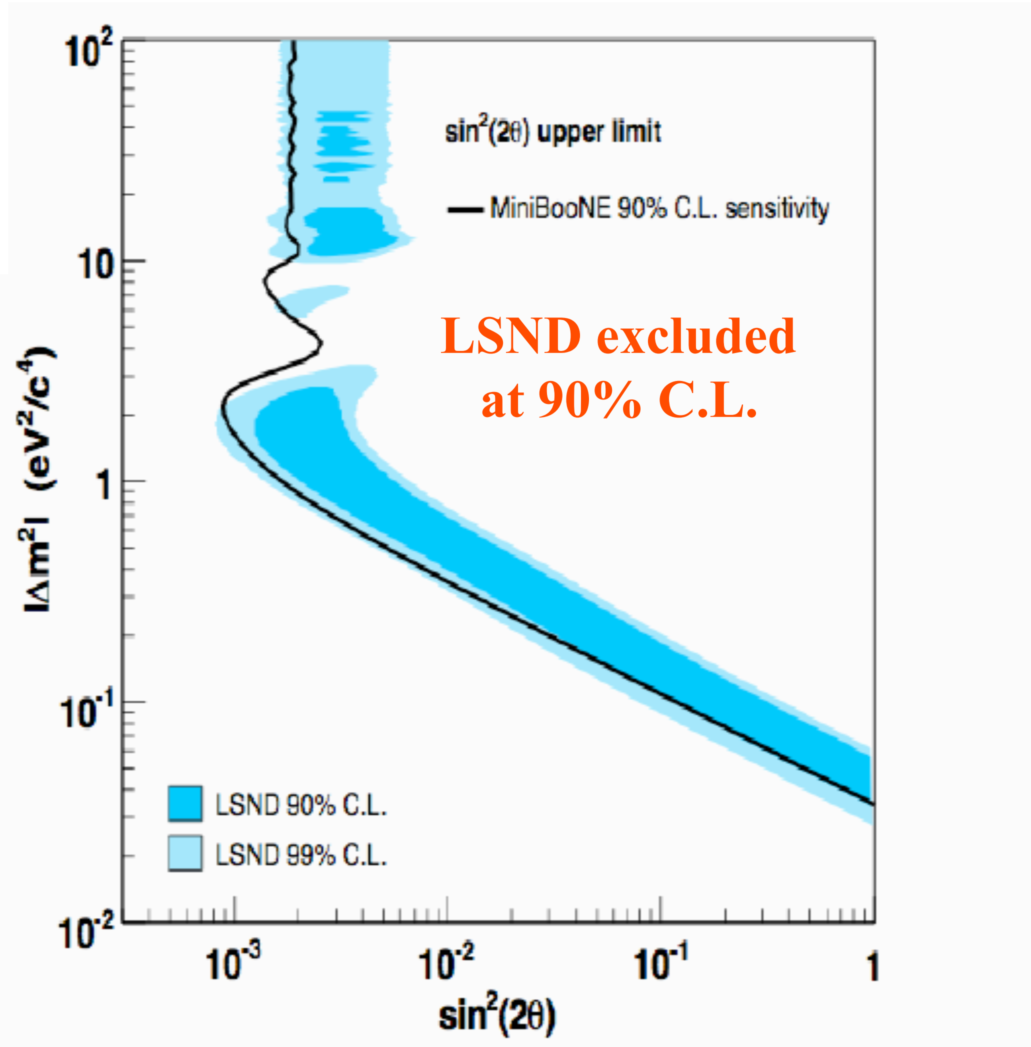
MiniBooNE: Opening the box

Limited oscillation analysis to E_ν > 475 MeV
(more background at lower energies)

Observe 380 events
Expected background:
358 ± 19 (stat) ± 35 (syst)

No oscillation signal.





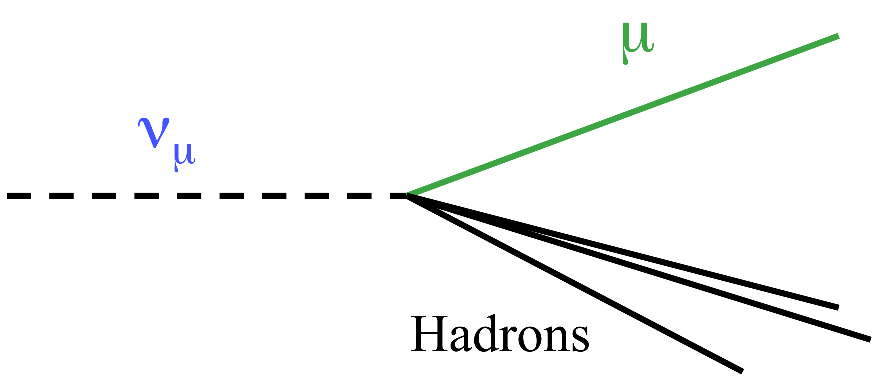
What's needed next?

- Confirm that ν_μ disappearance is really a $\nu_\mu-\nu_\tau$ oscillation. Accelerators.
- What is the absolute neutrino mass scale? β and $\beta\beta$ decay, cosmology
- Are neutrinos their own antiparticle? $\beta\beta$ decay
- Determine $\boldsymbol{\theta_{13}}$. Reactors, accelerators.
- Determine the mass hierarchy. Accelerators.
- Any CP violation in the neutrino sector? Accelerators.

Current programme

- Accelerator experiments: ν_τ appearance, θ_{13}, mass hierarchy , CP (?)
  - MINOS continuing
  - NOνA
  - T2K
- Reactor experiments: θ_{13}. Double Chooz, Daya Bay.
- Beta decay
- Double-beta decay
- Cosmology

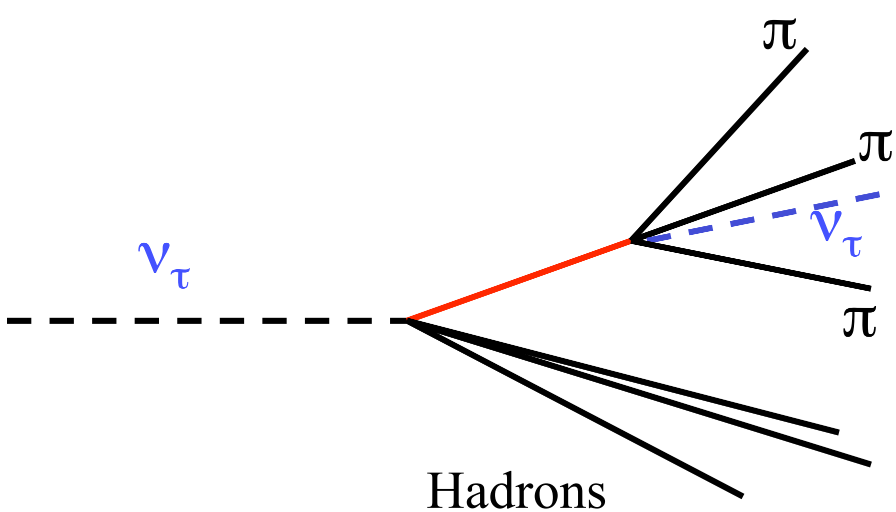
ν_μ CC vs ν_τ CC



ν_μ CC Interaction

Muon

Hadrons produced
close to each other
Back to back with muon



ν_τ CC Interaction

τ decay to hadrons ($\pi\nu_\tau$, $\pi\pi\pi\nu_\tau$,…))
65% Branching ratio
No Muon
They look like **NC events.**
and
Hadrons produced at main vertex
+ hadrons from **τ** decay
--->**Spherically symmetric** event
Secondary vertex

MINOS ν_τ appearance

- MINOS is doing a ν_μ disappearance experiment.
- Can it look for ν_τ's?
- Detector is too coarse to identify τ's produced in a ν_τ CC interaction by looking for secondary vertices or decay kinks.

- But: Use hadronic τ decays: **No muon in final state.**

- These decays look like neutral currents (NC) events.

- So if ν_μ ---> ν_τ expect **an increase in NC-like events**:
  - NC/CC > Expected NC/CC from standard ν_μ interactions.
  - But NC + CC **SAME** as for standard ν_μ .
- If ν_μ ---> **sterile neutrino**, the sterile does not interact at all.
  - (NC + CC) < for ν_μ and
  - NC/CC remains the **SAME** as for ν_μ .

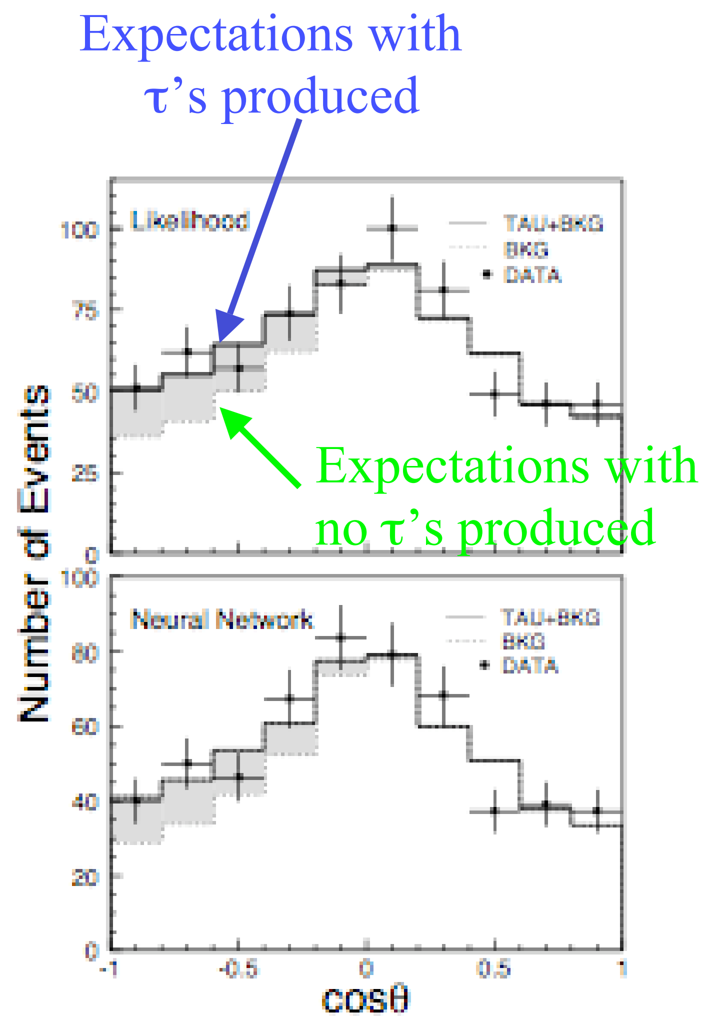
No result yet from MINOS

SuperKamiokande ν_τ appearance

- SK detects atmospheric ν_μ and ν_e
- Can it look for ν_τ's?
- Detector is too coarse to identify τ's produced in a ν_τ CC interaction by looking for secondary vertices or decay kinks.

- But: Use hadronic τ decays:

  No muon in final state.
- Use the fact that they are spherically symmetric.
- Select events with
  - No muon
  - Many rings
  - Distributed spherically symmetric
- Use likelihoods or neural network.



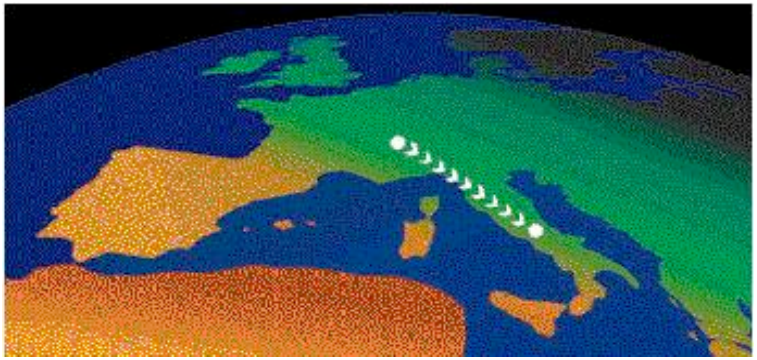
Expect 78±26 τ events for $\Delta m^2 = 2.4 \times 10^{-3}\ eV^2$

Observe $136 \pm 48(\mathrm{stat})_{-32}^{+15}(\mathrm{syst})$

Disfavours NO τ appearance by 2.4 σ

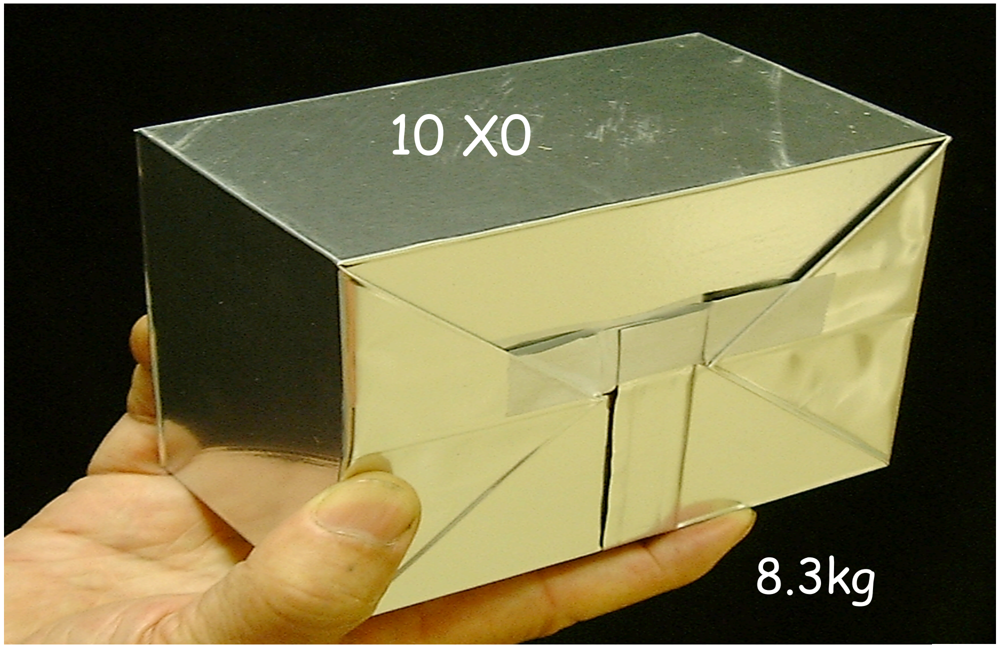
OPERA ν_τ appearance: the definitive experiment

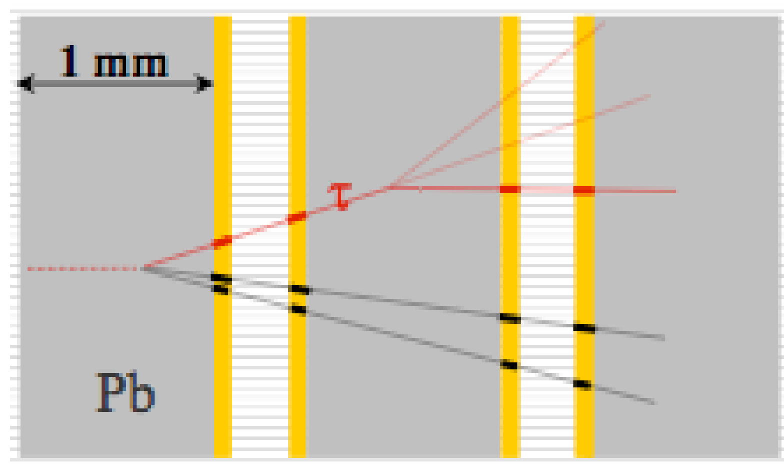
- Atmospheric ν_μ disappearance occurs at L/E ~ (GeV)/ (~1000km)
- Distance from CERN to Gran Sasso Lab (LNGS) in a road tunnel in Italy = 732km
- Send a ν_μ beam (~ 20 GeV) from CERN to LNGS.



- Search for ν_τ appearance.
- Look for events with **SECONDARY VERTICES OR KINKS**
- Using photographic emulsions

The lead-emulsion brick

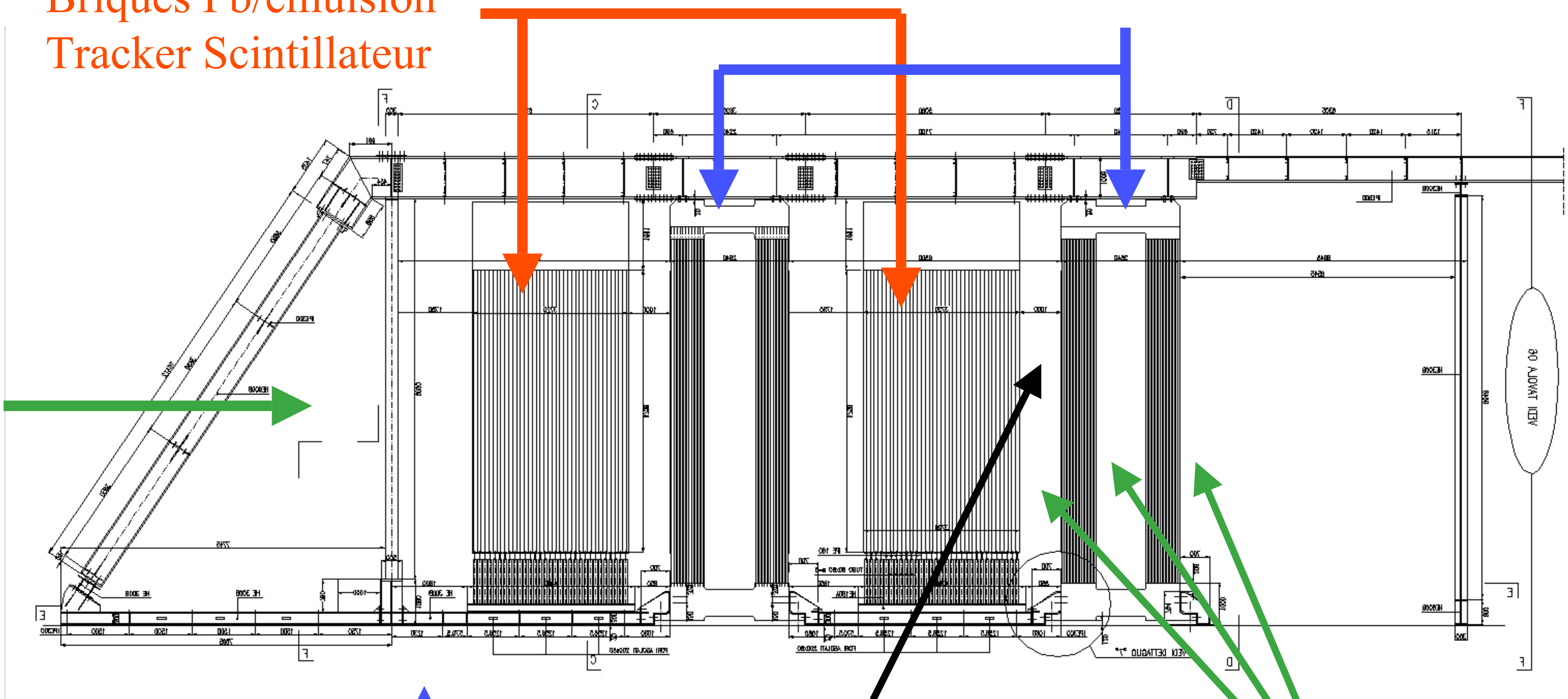




Le détecteur : 2 super-modules

31 plans dans chaque supermodule:
Un plan:
Briques Pb/émulsion
Tracker Scintillateur

Aimant
+ RPC's en bakélite



Veto:
RPC's en verre

XPC: RPC's
Strips croisées

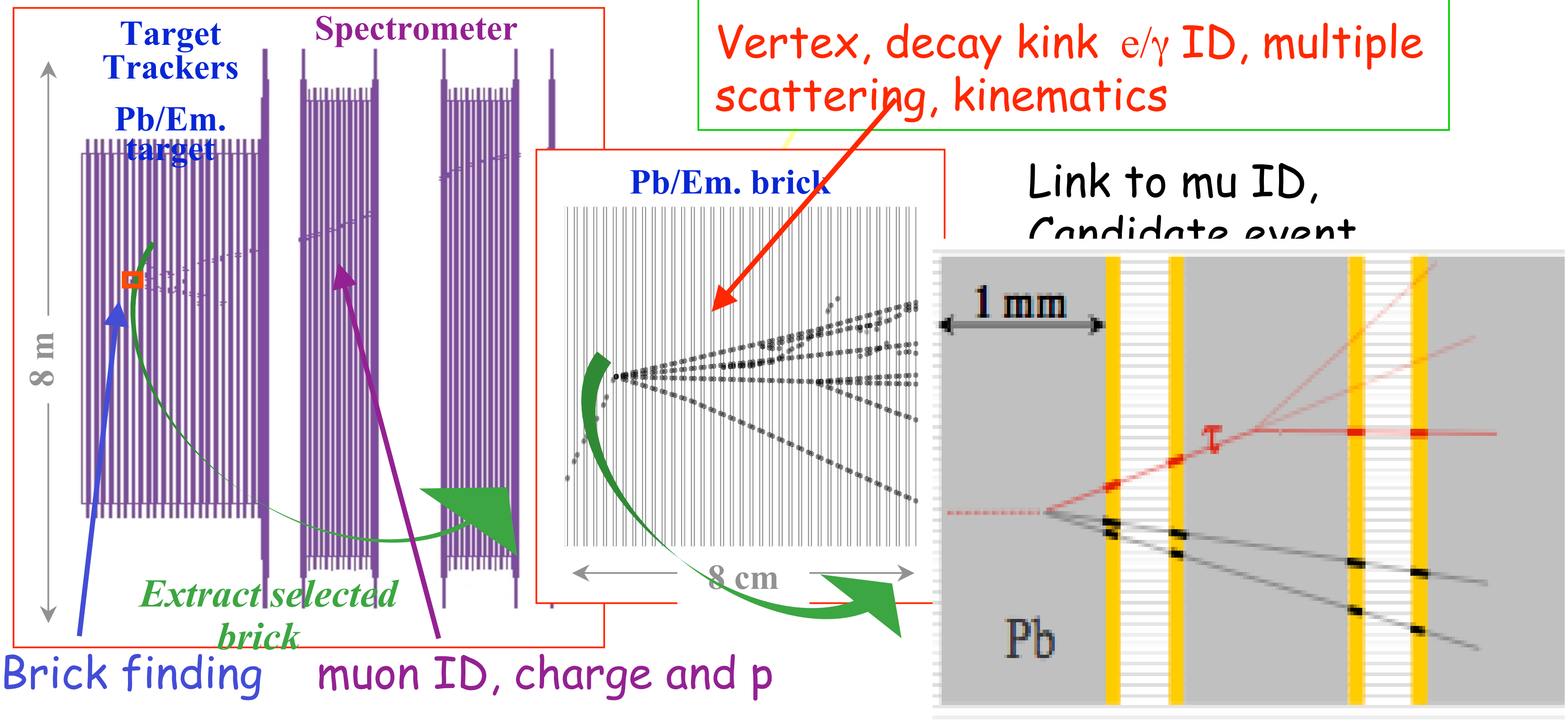
HPT:Tracker de Haute Précision
Tubes à dérive

OPERA

Electronic detectors:

Emulsion analysis:

Vertex, decay kink e/γ ID, multiple scattering, kinematics

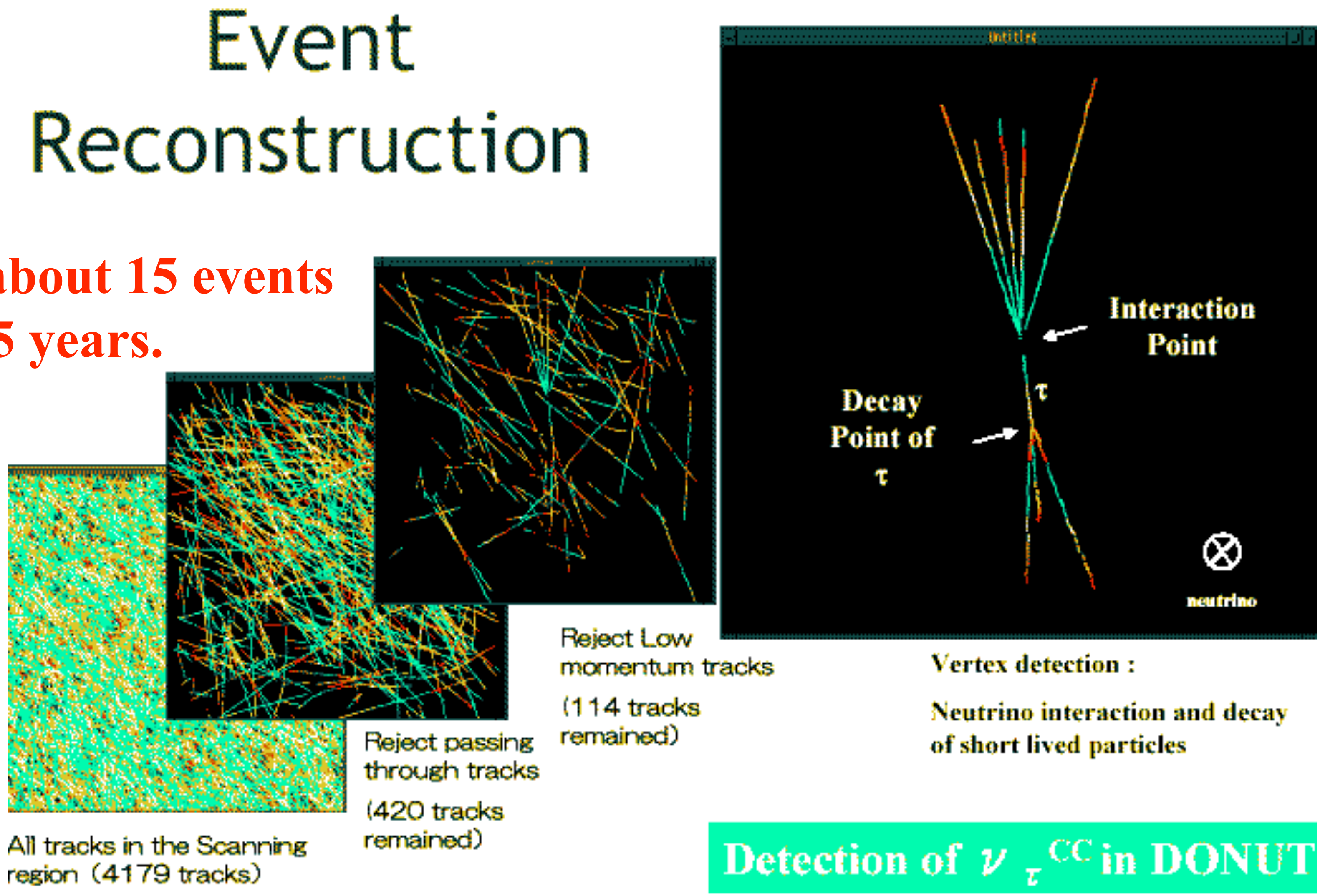


Using the scintillator planes, reconstruct the event vertex
---> determine the interaction brick. Extract it. ~ 30 bricks / day

Expose the brick to cosmic rays
to have tracks going through all sheets
For relative alignment
Develop the emulsion sheets

OPERA

Expect about 15 events in 5 years.

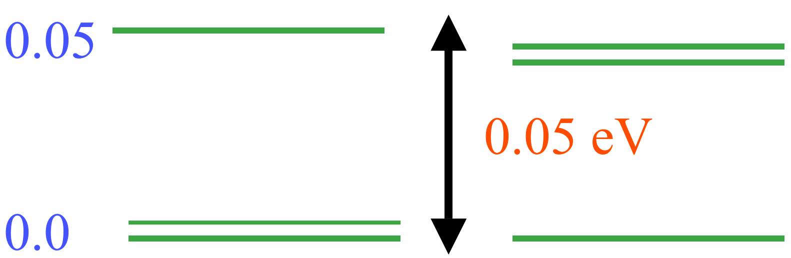


Absolute neutrino masses

- What are the absolute neutrino masses?

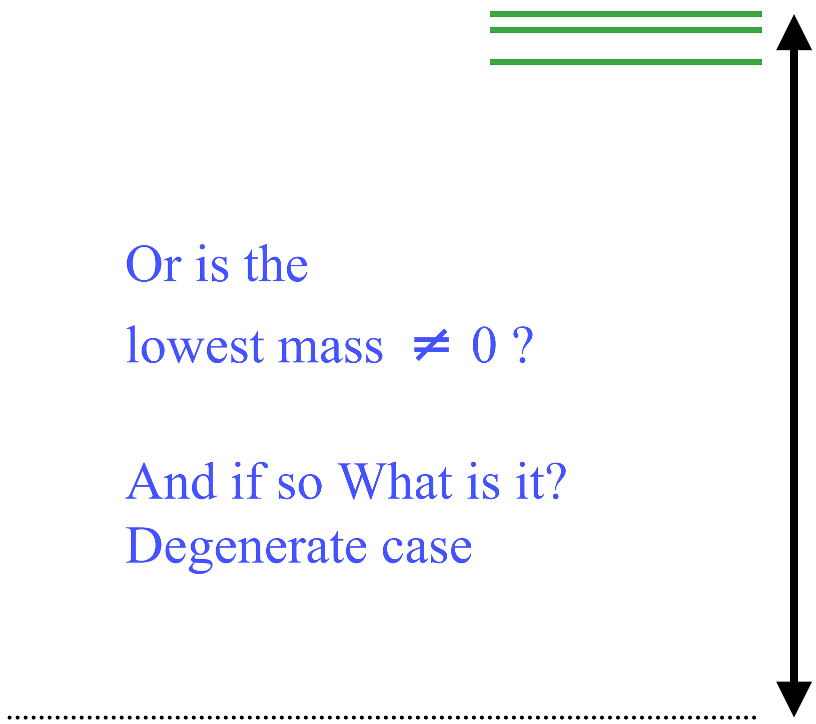
At least one neutrino
Must have a mass
$>(\mathbf{2.4 \times 10^{-3}})^{1/2} > 0.05$ eV

But is the lowest mass
ZERO?



Or is the
lowest mass $\neq 0$?

And if so What is it?
Degenerate case



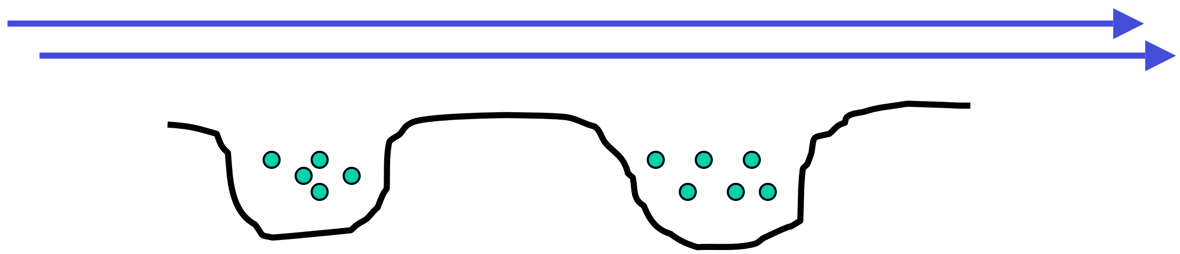
Absolute neutrino masses

Three ways to determine them:

- Cosmology
- β-decay: Tritium end point
- Double-β decay

Cosmology

- Structure formation evolves with time since the big bang:
  they get **bigger** with time.
- If relativistic, neutrinos will be free-streaming. They will not be trapped in a gravitation well.

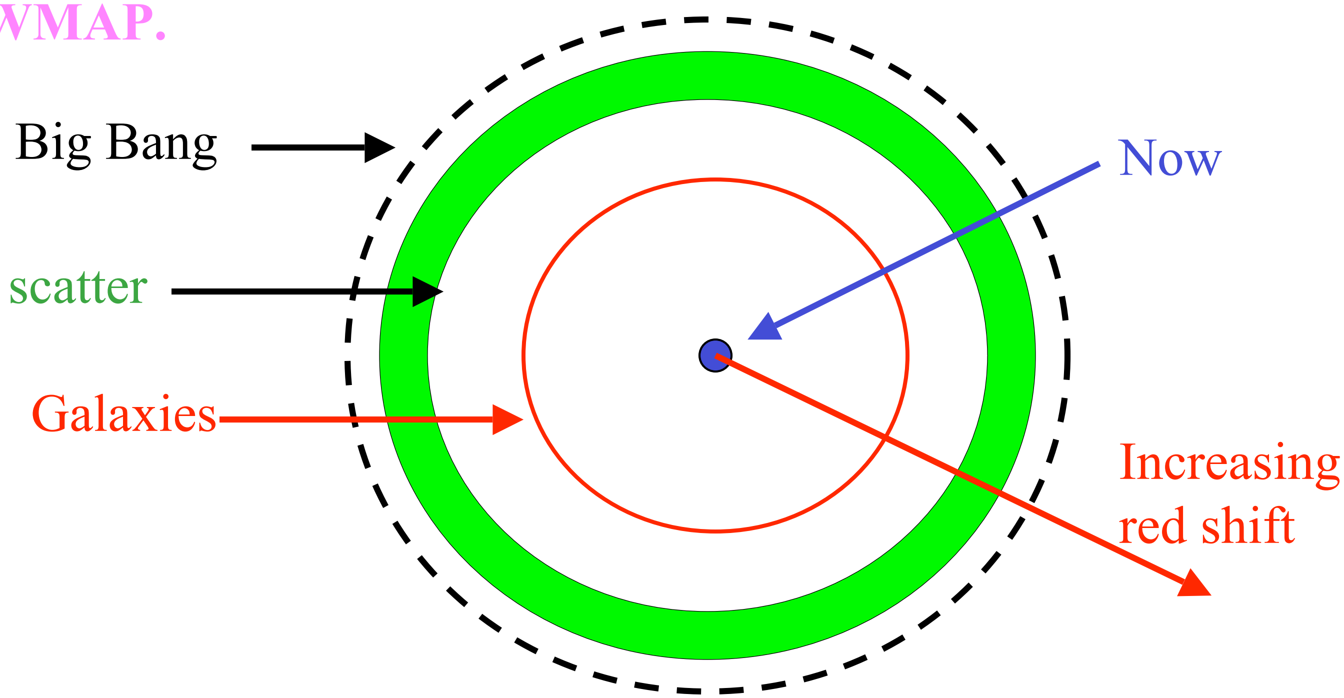


- This means that they will not contribute their mass to the gravitational attraction forming clusters.
- They will start to do so only as they become non-relativistic.
- The **larger** their mass, the **earlier** they will become non-relativistic as the universe cools.
- The **smaller** the clusters they will affect.

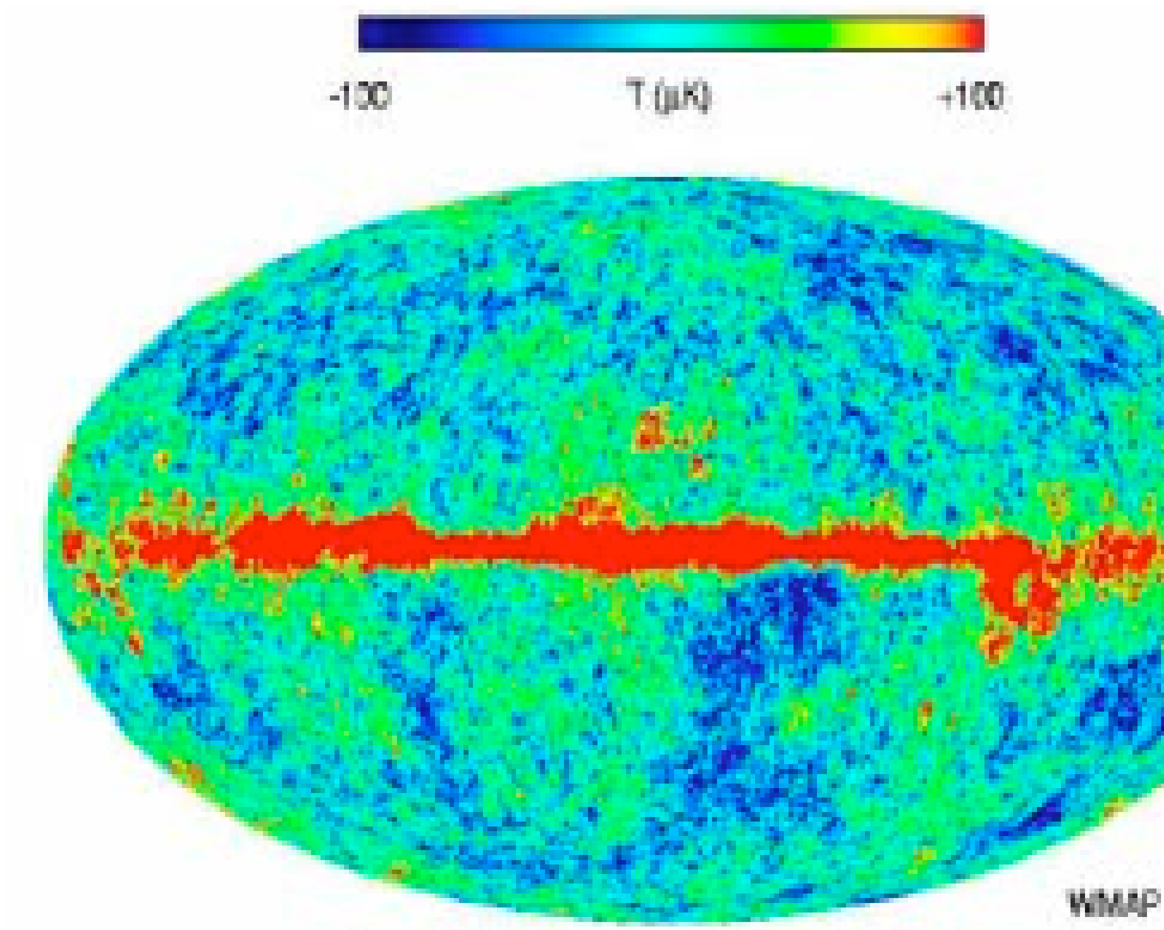
- **So massive neutrinos can affect cluster formation at small scales.**

How do we measure cluster sizes?

- At very large scales, measure the distribution of galaxies:
  Sloan Digital Sky Survey.
- At smaller scales study the distribution and temperature of Cosmic Microwave Background Radiation (CMBR) .
  This gives the location of the "last scatter".
- Also CMBR photons scattering on electrons become polarized.
- Amount of polarization gives the density of electrons at the "last scatter".
- This was done by **WMAP.**



WMAP:Temperature fluctuations in CMBR



Measure them by recording
The black-body spectrum.

They vary by ~ 10^{-5} !

Map of CMBR temperature Fluctuations

$$\Delta(\theta,\varphi) = \frac{T(\theta,\varphi) - \langle T \rangle}{\langle T \rangle}$$

Multipole Expansion

$$\Delta(\theta,\varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\varphi)$$

Temperature --> cluster size?

- Denser matter causes more heating raising temperature of photons.
- Competing effect:
  - the photon traverses a region of matter.
  - It falls in its gravitational potential.
  - By the time it comes out of the region, the region has acquired more mass.
  - The gravitational potential the photon has to climb out of is deeper than the one it fell in: it loses energy: it is red-shifted. It is cooler.
- Net effect: **cooler temperatures mean denser matter.**

How to observe matter fluctuations

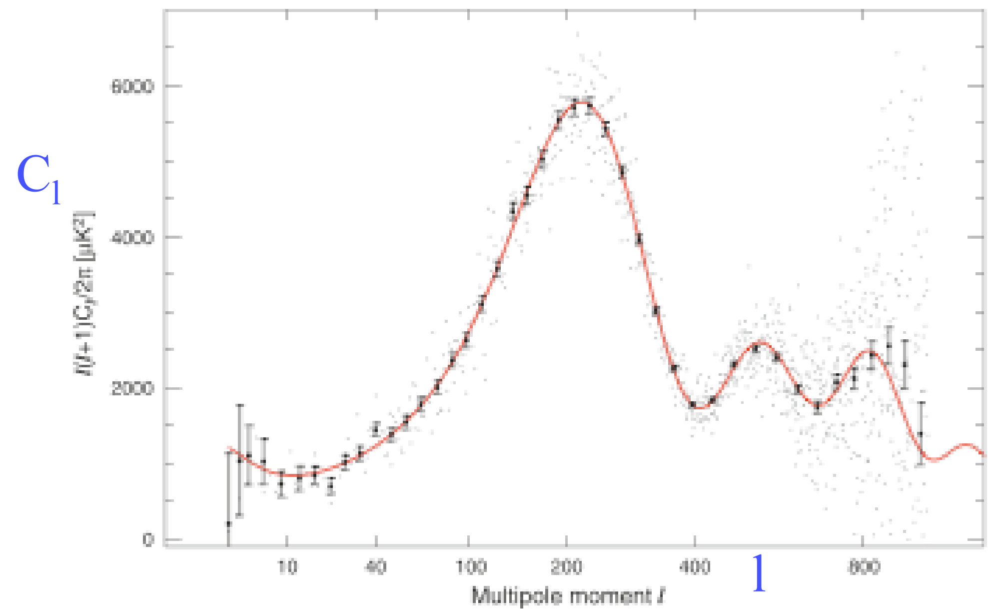
- WMAP has an angular resolution of 10'.
- Measure temperature distribution over the whole sky.
- Measure the deviation from the average temperature for each point: **$\Delta T/T$.**
- Collect the temperature for all pairs of direction **n**,**m** separated by angle $\boldsymbol{\theta}$.

  (n.m = cos **θ)**.
- Measure the correlation between these two points by forming the average

- $C(\boldsymbol{\theta}) = \langle (\Delta T(\mathbf{n})/T)(\Delta T(\mathbf{m})/T) \rangle$

- If there is no correlation $C(\boldsymbol{\theta})$ will be zero. **Not so otherwise**.
- Repeat for all angles **θ.**
- Expand as a series of Legendre polynomials $P_l(\cos\theta)$
- $C(\boldsymbol{\theta}) = (1/4\pi) \sum(2l+1)\, \mathbf{C_l}\, P_l(\cos\theta)$. Summed fro l to l_{max}.
- $\mathbf{C_l}$ describe the density fluctuations.
- The sum falls off to zero at ~ $200^o/l_{max}$.
- The relevant scale for primordial fluctuations is ~ 1^o, so $l > 100$ is the interesting region.

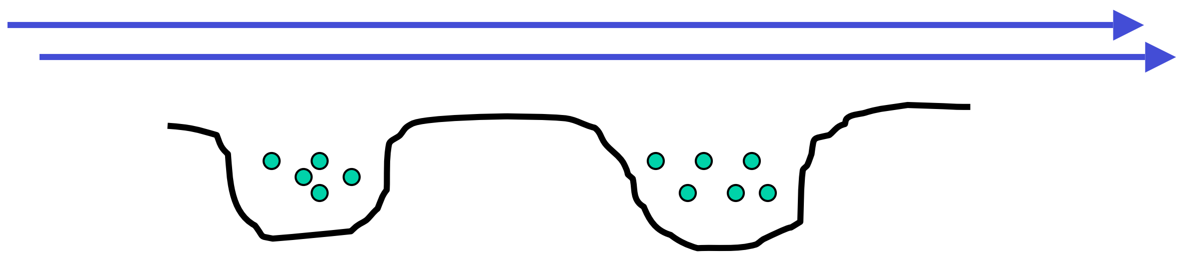
Limits



Smaller scales ---->

- Plot Power ~ C_l vs l . Observe peaks.
- Assume there has been an initial primordial perturbation in the density.
- Can be decomposed into a superposition of different wave lengths λ.
- The first peak will correspond to a wave that has had time to oscillate just once.
- A "recent wave" corresponding therefore to a time when structures were large.
- The second more than once. "Older wave". etc… **larger l ---> smaller structures.**

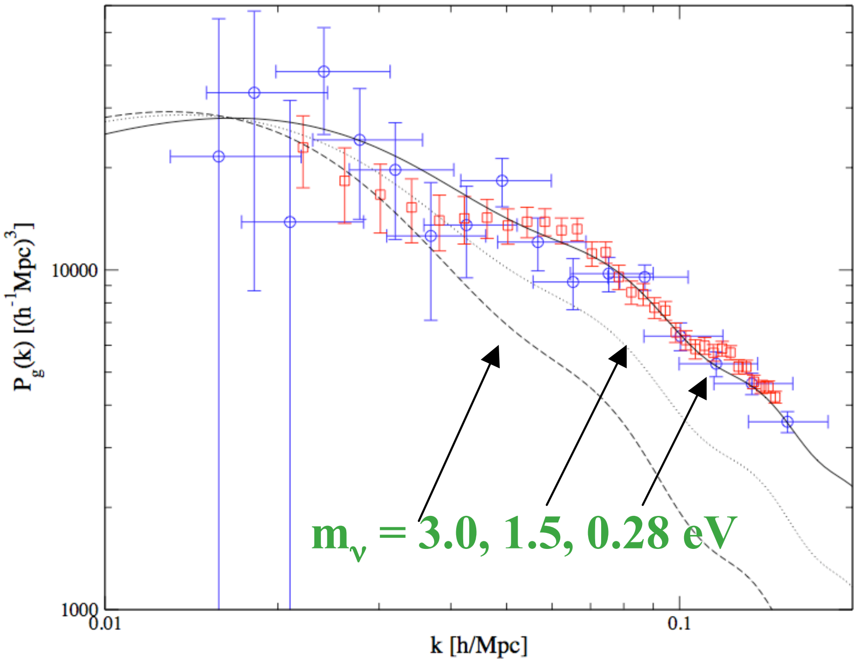
Limits

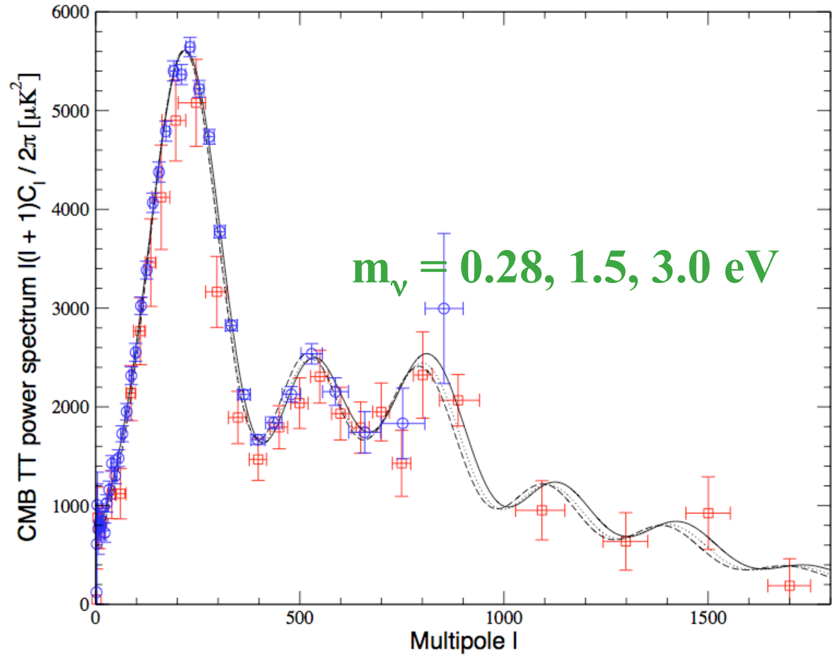


- If relativistic, neutrinos will be free-streaming. They will not be trapped in a gravitation well.
- This means that they will not contribute their mass to the gravitational attraction forming clusters.
- They will start to do so only as they become non-relativistic.
- The **larger** their mass, the **earlier** they will become non-relativistic as the universe cools.
- The **smaller** the clusters they will affect.

- **So massive neutrinos can affect cluster formation at small scales.**

Limits





Smaller scales ---->

Smaller scales ---->

Can do the same with galaxy clusters and super clusters:

Look at fluctuations in the number of galaxies in volumes of λ^3 Mpc in sky. Vary λ.

Limit on absolute neutrino mass

$$\Sigma\ m_1+m_2+m_3 < 1.3\ \text{eV}$$

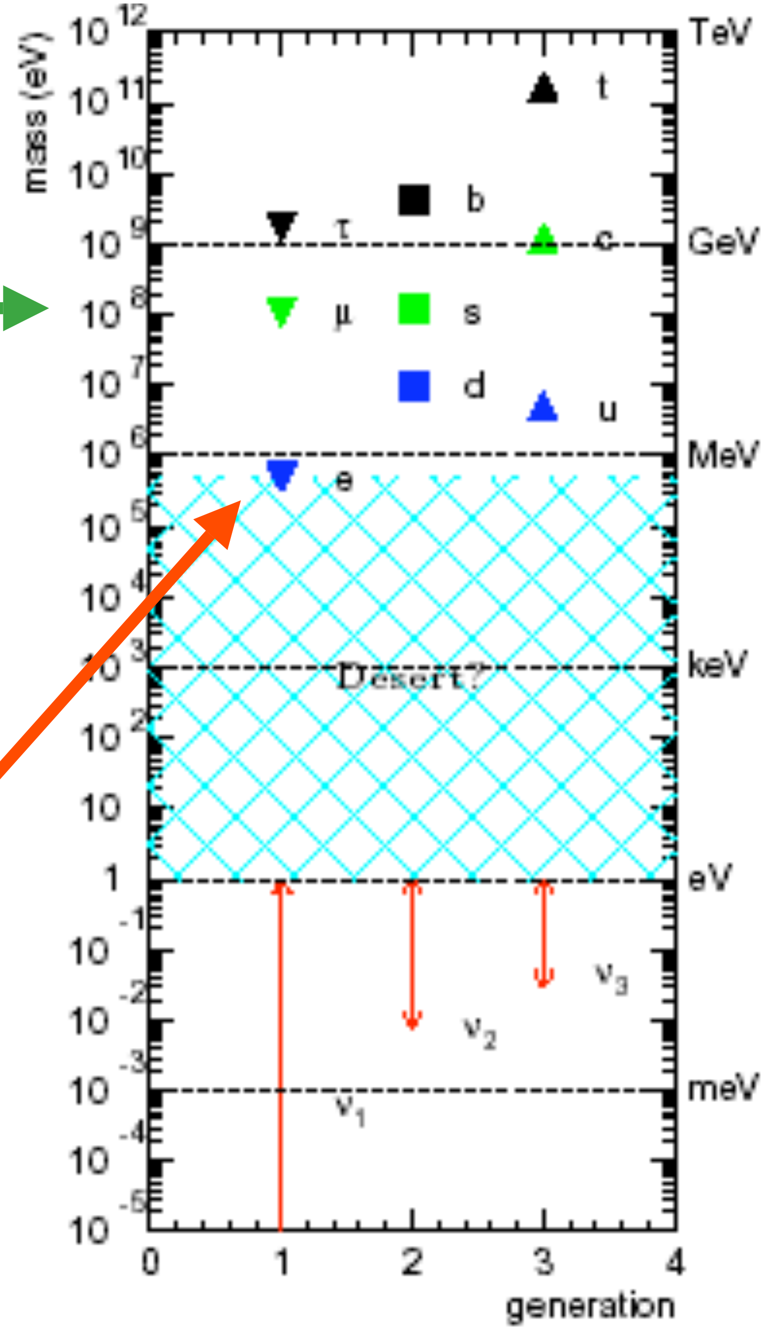
From cosmology (WMAP alone)

Remember: we also have a lower limit : > 0.05 eV

on at least one neutrino mass state

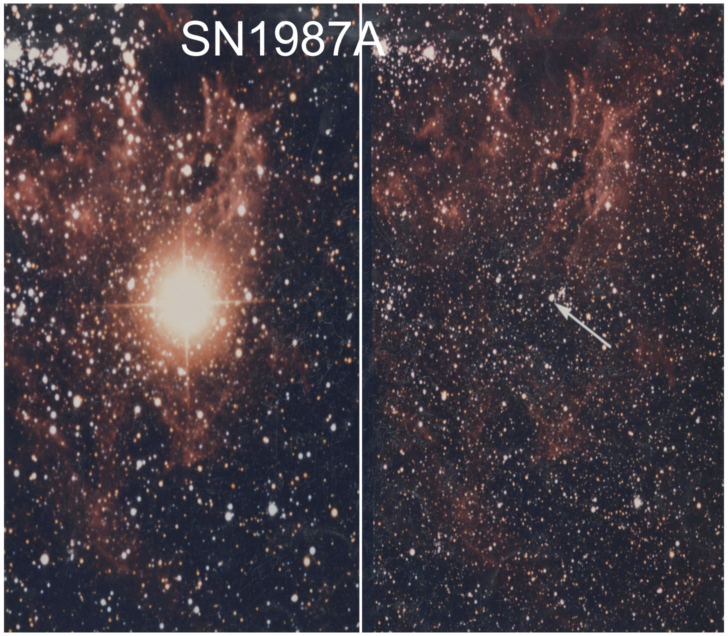
Other particles

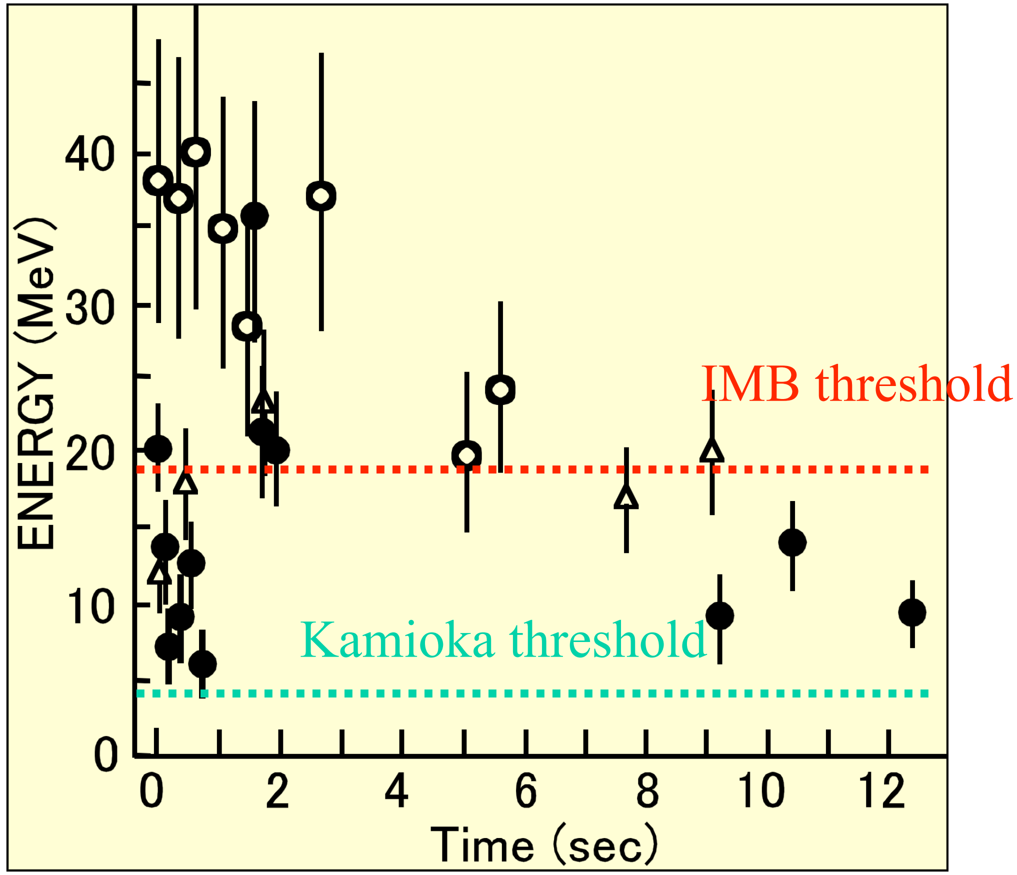
Why are neutrino masses so low????
6 orders of magnitude smaller than the next heaviest particle: the electron



Fascinating to me !!!!!!

Neutrinos from Super Novae





A large burst of neutrinos is associated with a SN

Collapse of the iron core (R = 8000 km) of a star due to gravitational pressure:

$p + e^- \text{--->} n + \nu_e$

Turns into a neutron star (R = 50 km) with density of nuclear matter $10^{14\text{-}15}$gm.cm^{-3}

About **20 neutrino interactions** seen mostly in Kamiokande, also IMB.

Absolute Neutrino Mass from Super Novae

Time of arrival distribution ---> limit on **ν** mass.

Time difference between a c=1 neutrino and a massive neutrino:

$$\Delta t = D/\gamma c - D/c = (1/\gamma - 1)(D/c) = (E/p - 1)(D/c) = m^2 D/(2E^2)$$

$$= 2.57\ (\text{sec})\ (D/50\text{kparsec}))\ (10\text{MeV}/E)^2\ (m_\nu/10\text{eV})^2\ (\text{In REAL units})$$

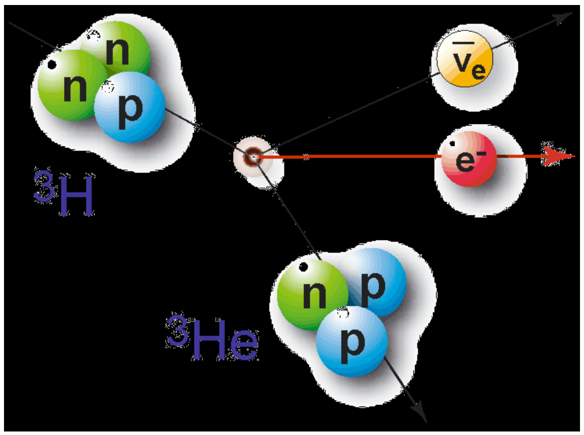
$$m_\nu < 20\ \text{eV}$$

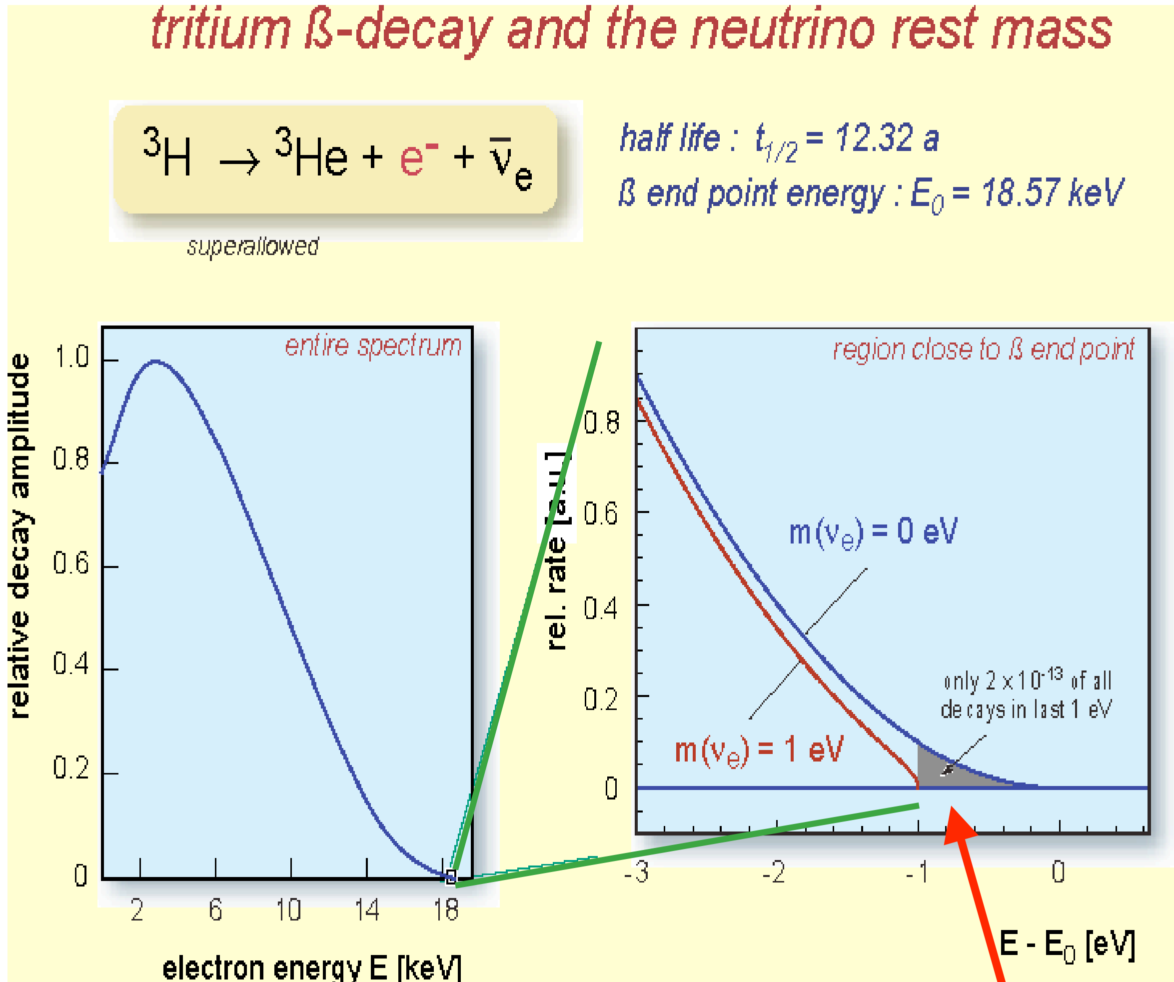
This could be used in the future, now that we have better detectors
IF another SN occurs, SuperKamiokande could see **5500** events.

Problem: Uncertainty in emission time distribution.

The direct measurements: ν_e

Look at the end point energy in a β decay spectrum: Tritium





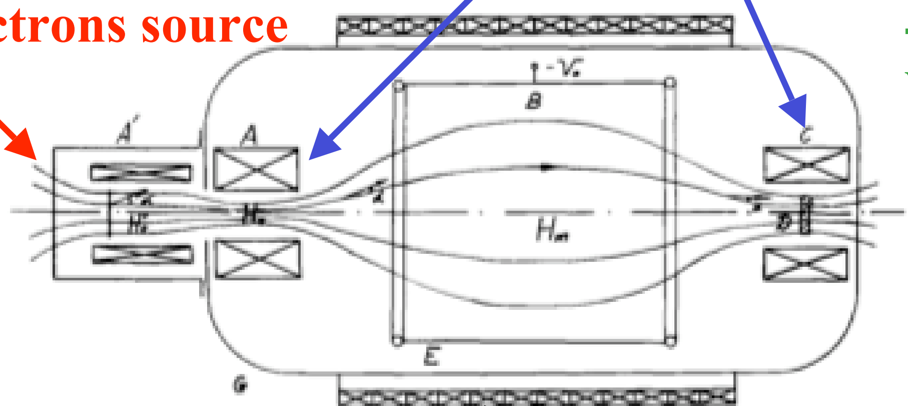
If $\mathbf{m_\nu \neq 0}$ the maximum possible energy carried by the electron will be **reduced**

Magnetic Adiabatic Collimation Electrostatic Filter (MAC-E)

Two superconducting solenoids
--> guiding magnetic field

At centre of spectrometer B drops by several orders of magnitude
Transverse motion
---> longitudinal motion.
Wide parallel beam

β electrons source



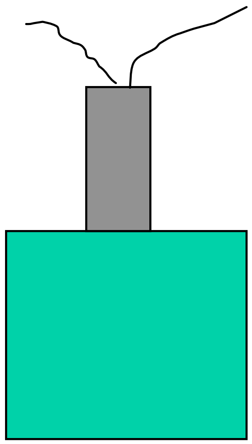
X

Those that do, reach detector

Cylindrical electrodes
Apply E field to let electrons with energy > E_{min} go through
By gradually increasing the E field, scan the whole β spectrum

New technique: cryogenic bolometer

Cryogenic detector principle:
Make the absorber out of a dielectric
and diamagnetic material
Particle deposits an amount of energy Q
Heat capacity C_v is proportional to T^3.
At very low temperature it will be small
So $\Delta T = Q / C_v$ will be measurable



^{187}Re has 7 times smaller end-point than Tritium: Good

Can use a cryogenic bolometer to measure total energy emitted.

Still working on energy resolution

Problem: measures ALL decays simultaneously.
Cannot select JUST events near end-point

So must collect 10^{10} more events than needed (but Deadtime ~100μs).
Many detectors needed.

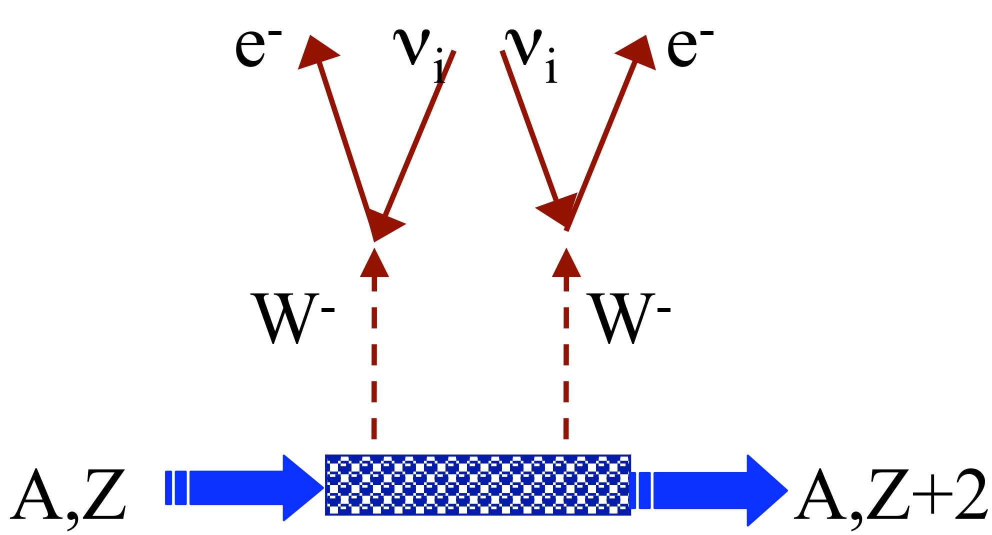
The direct measurements

	ν_e	ν_μ	ν_τ
Limit	2.3 eV/c^2	0.16 MeV/c^2	18.2MeV/c^2
Confidence Level	95%	90%	95%
Method	Tritium End point	p_μ in π-->$\mu\nu_\mu$	5 pion inv. mass in decay τ --> $5\pi\ \nu_\tau$

Double-β decay

(A,Z) → (A,Z+2) + 2 e^- + 2**ν**

Standard 2-neutrino **double β decay**: emits 2 electrons.
Two separate neutrons decaying in nucleus.
This happens when **single β decay** is energetically forbidden
or inhibited by parity or angular momentum
Typical half-lives: **10^{19} - 10^{21} years**



Neutrinoless Double-β decay

(A,Z) → (A,Z+2) + 2 e^-

- Since neutrinos have non-zero mass.

- They therefore can develop a **right-handed** helicity component **$\sim m_\nu/E_\nu$.**

- IF the neutrino is its own antiparticle

Neutrino is **IDENTICAL** to antineutrino

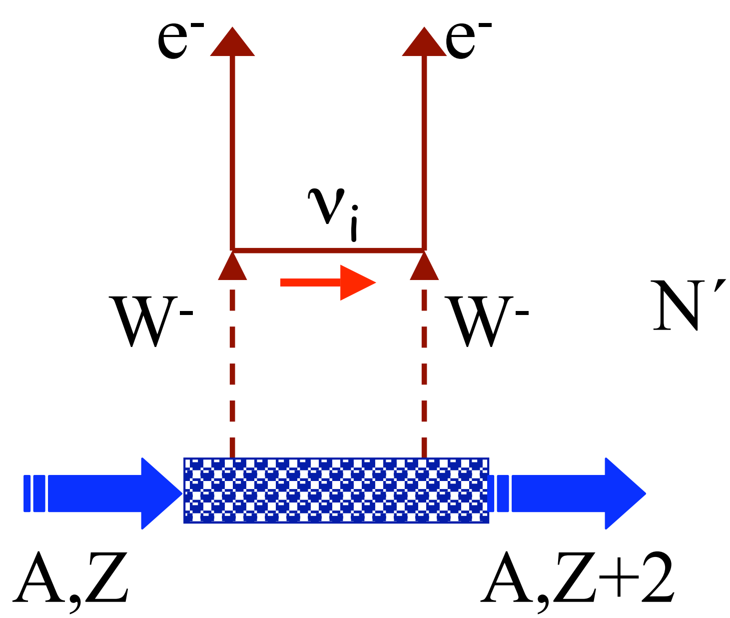
Then the right handed component of the **ν** emitted in the first neutron decay IS an **antineutrino**

Exactly what could be reabsorbed by the W^- of the second decay

- Helicity must flip

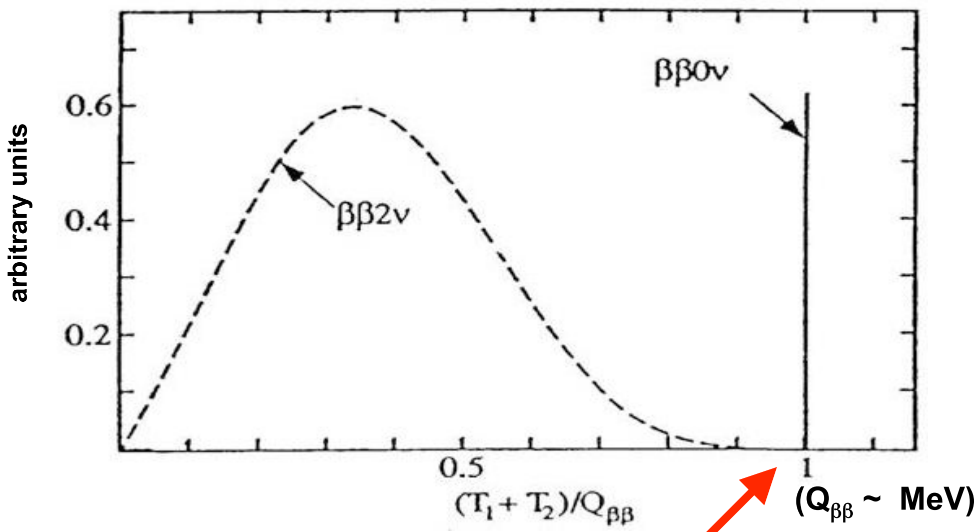
→**Probability increases with m_ν.**

Neutrinoless double **β** decay



If the neutrino is its own Antiparticle: Majorana neutrino.

Detection



Only **2 electrons** are emitted:
The sum of their energy
is **monochromatic**:
Difference of the
(A,Z) - (A,Z+2) masses
Equal to the end-point of the
2-neutrino beta-decay.

Look for a peak at the end point
of the 2-neutrino **β** spectrum

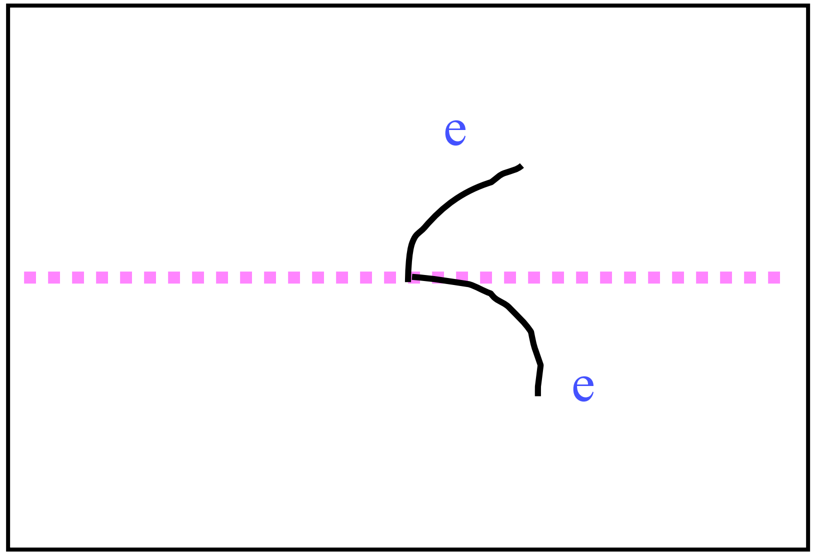
New experiments will use: ^{130}Te, ^{132}Xe, ^{76}Ge, ^{100}Mo

Will observe the 2 electrons through
bolometric, calorimetric or tracking techniques

Sensitivity down to 100-300 meV. Note: “m” stands for milli

Detection Technique I

Source ≠ detector



Source is a sheet of Double-β decay material.

Sheet must be thin to minimize energy loss of 2 electrons: affects energy resolution.

Placed inside a tracking device.

Observe the two electrons

Measure their energy (and direction).

Good for background rejection:

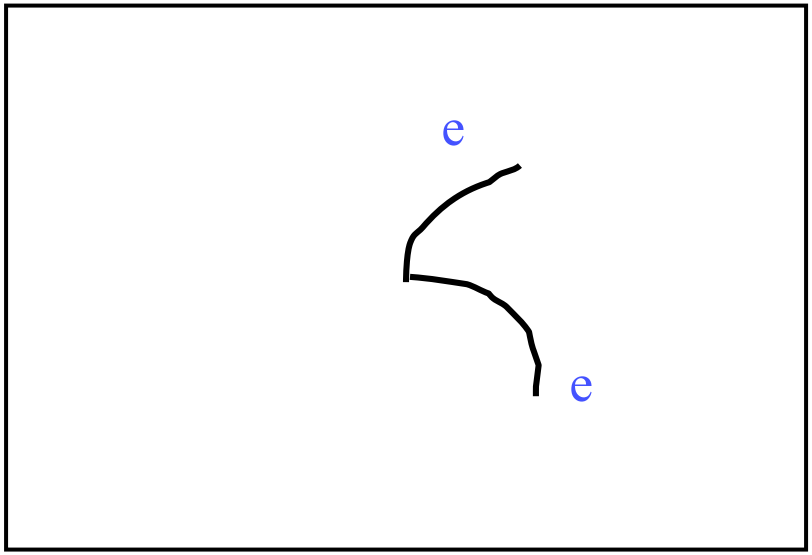
2 electrons must originate from same spot.

Detection Technique II

Source = detector

Material is part of a calorimeter.

It measures the whole energy of the two electrons: no problem of energy loss.



Cryogenic detector

Dielectric material for which

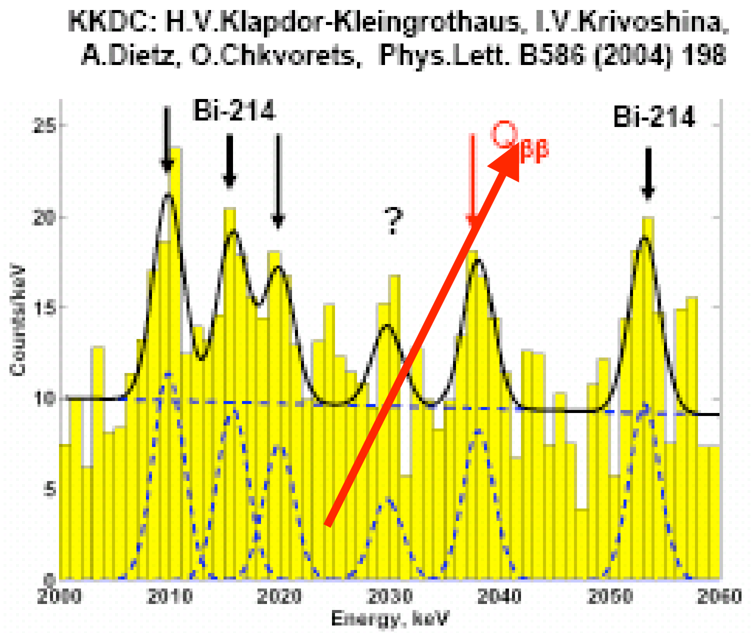
heat capacity is proportional to T^3

At very low temperature, a small energy deposit can result in a large temperature increase.

Limits and one possible claim

Present limits on neutrinoless double beta decay: 10^{21} - 10^{25} years

Except for one claim using 11 kg of enriched ^{76}Ge:



Half life $T^{0\nu}_{1/2}$: $1.19^{+2.99}_{-0.50}$ years

- Many other peaks, maybe explained
- Where should the flat background line be drawn?

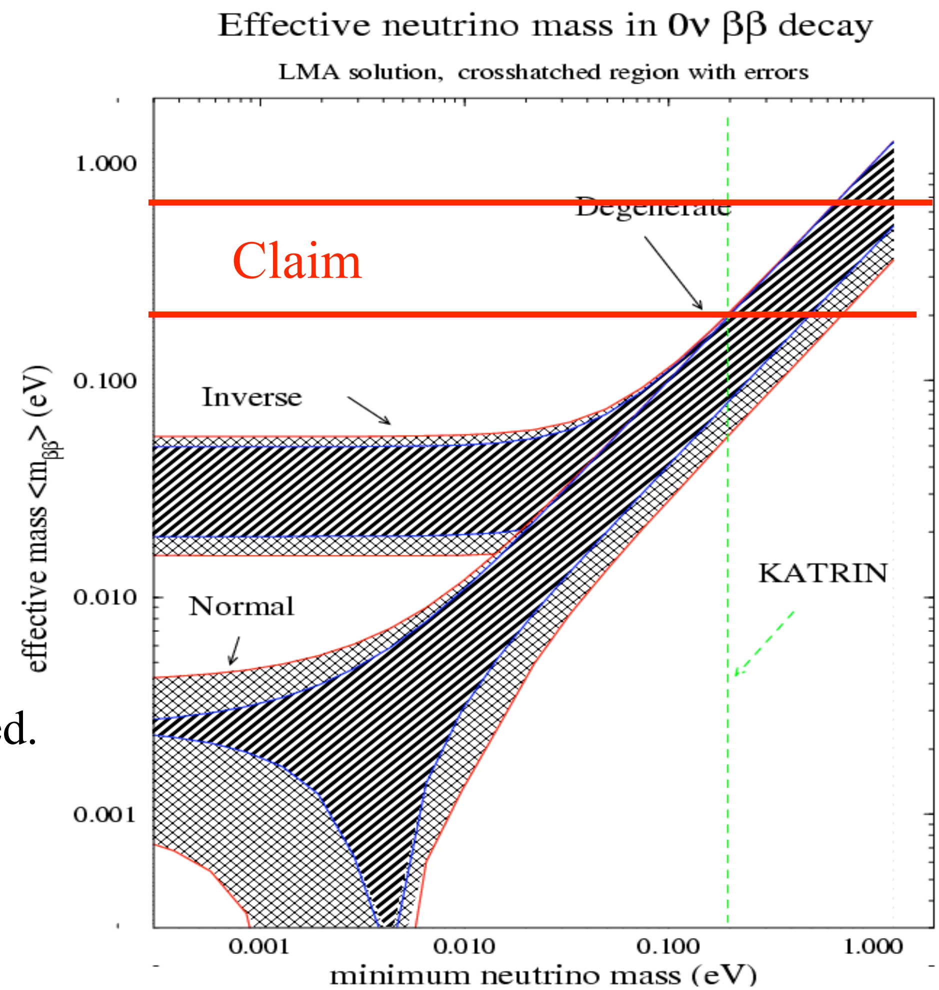
Needs checking

Limits

Rate = $(T^{0\nu}_{1/2})^{-1}$ = (Phase space factor) x (Matrix element)^2 x $\langle m_{ee}\rangle^2$

$\langle m_{ee}\rangle = | U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3 |$

- **Normal hierarchy**: $m_3 > m_{1,2}$
  But U_{e3} is small so large m multiplied by small U --> **small m_{ee}.**
- **Inverted hierarchy**: $m_{1,2} > m_3$
  So larger U_{ei} multiplied by large $m_{1,2}$ ---> **large m_{ee}**
- **Degenerate**: all 3 masses ~ same
  No difference between normal and inverted.



Present limits

Rate = $(T^{0\nu}_{1/2})^{-1}$ = (Phase space factor) x (Matrix element)^2 x $<m_{ee}>^2$

Nuclear matrix elements are still uncertain. Affect Lifetime limits.

Best limits from **^{76}Ge > 1.9 x 10^{25} years**

$0.30 < m_{ee} < 1.04$ eV

New experiments will go down
100-300 milli eV

Reminder: **If Neutrinoless ββ decay is found,**
the Majorana nature of neutrinos will have been established.

The NEAR Future

Correlations in Oscillation Probability

From M. Lindner:

- $\Delta = \Delta m^2_{31} L/4E$
- qualitative understanding $\Rightarrow$ expand in $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin^2 2\theta_{13}$
- matter effects $\hat{A} = A/\Delta m^2_{31} = 2VE/\Delta m^2_{31}$; $V = \sqrt{2} G_F n_e$

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) \approx\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
& \pm \sin\delta_{CP}\ \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
& + \cos\delta_{CP}\ \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
& + \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

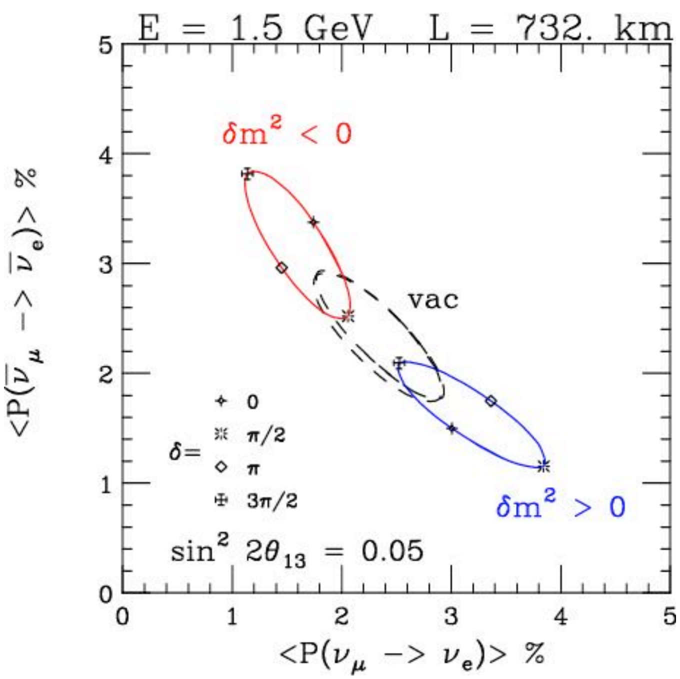
Measuring P ($\nu_\mu \sim \nu_e$) does NOT yield a UNIQUE value of θ_{13} .
Because of correlations between θ_{13}, δ_{CP} and the mass hierarchy (sign of Δm^2_{31})

CP violation: Difference between Neutrino and Antineutrino Oscillations

Mass hierarchy accessible through Matter effects :
1 - $\hat{A}$ depends on sign of $\Delta m_{31}{}^2$

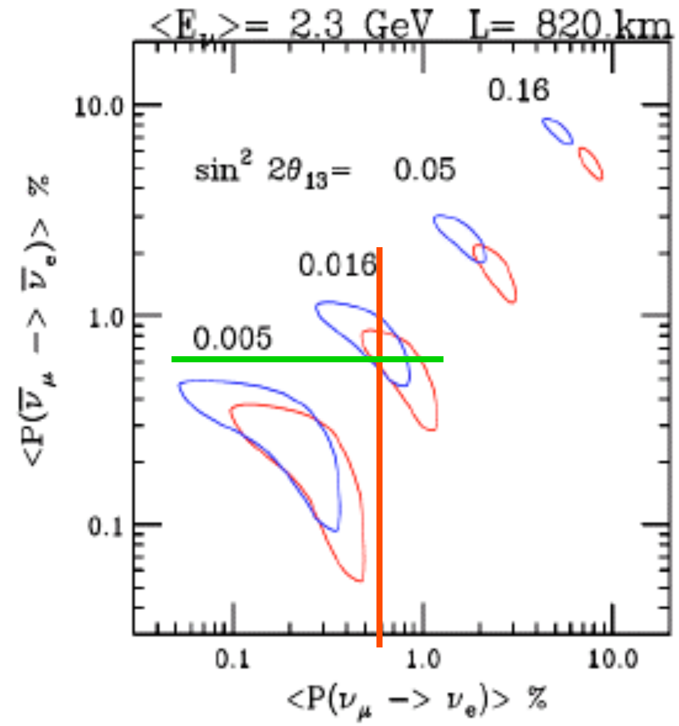
8-fold degeneracies

- θ_{13} - δ ambiguity.
- Mass hierarchy two-fold degeneragy



A measure of $P_{\mu e}$ can yield a whole range of values of θ_{13}

Measuring with $\bar{\nu}$'s as well reduces the correlations



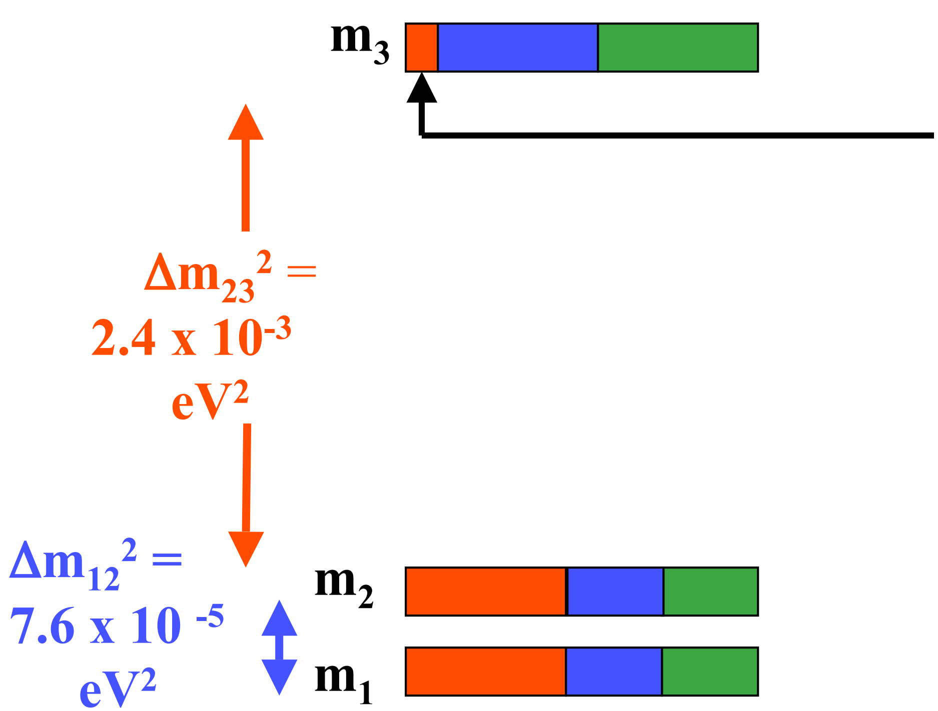
- θ_{23} degeneracy:

For a value of $\sin^2 2\theta_{23}$, say 0.92, $2\theta_{23}$ is 67° or 113° and θ_{23} is 33.5° or 56.5

- In addition if we just have a lower limit on $\sin^2 2\theta_{23}$, then all the values between these two are possible.

How do we determine θ_{13}?

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



- m_3 has a small piece of ν_e
- Amount: $|U_{e3}|^2 = \sin^2\theta_{13}$
- m_3 is only connected to other mass states through the

  atmospheric $\Delta m^2 = 2.4 \times 10^{-3}\ eV^2$
- Need an experiment with

  L/E ~ 500 km/GeV or m/MeV
- Must involve ν_e (or $\bar{\nu}_e$).

θ_{13} with Reactors

- Because of the large mass of μ (105 MeV) and τ (1777 MeV), we cannot look for ν_μ or ν_τ appearance with 3-4 MeV reactor antineutrinos.
- Must look for the disappearance of **anti-ν_e's.**
- At distances relevant to reactors (<100km), matter effects are negligible.
- $P(\nu_e \dashrightarrow \nu_x) = 1 - P(\nu_e \dashrightarrow \nu_\mu) - P(\nu_e - \nu_\tau)$

  With $\Delta_{ij} = \Delta m^2_{ij} L/4E = 1.27\, \Delta m^2_{ij}(eV^2) L(m)/E(MeV)$
- $P(\nu_e \dashrightarrow \nu_x) =$

  $1 - \sin^2 2\theta_{12}\, c_{13}^4 \sin^2\Delta_{21} - \sin^2 2\theta_{13}\, c_{12}^2 \sin^2 \Delta_{31} - \sin^2 2\theta_{13}\, s_{12}^2 \sin^2 \Delta_{32}$

  If we set $\Delta_{31} = \Delta_{32}$
- $P(\nu_e \dashrightarrow \nu_x) = 1 - \sin^2 2\theta_{12}\, c_{13}^4 \sin^2\Delta_{21} - \sin^2 2\theta_{13}\, (c_{12}^2 + s_{12}^2)\sin^2 \Delta_{32}$
- $P(\nu_e \dashrightarrow \nu_x) = 1 - \sin^2 2\theta_{12}\, c_{13}^4 \sin^2\Delta_{21} - \sin^2 2\theta_{13} \sin^2 \Delta_{32}$
- If we chose E and L to be at maximum of atmospheric oscillation length
- **We can even neglect the first term**

θ_{13} with Reactors: How to reduce systematics

$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2 [(\Delta m_{23}{}^2 L)/(4E_\nu)]$ near oscillation maximum

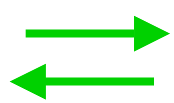
Advantage: NO dependence on δ_{CP} or mass hierarchy: No ambiguities.

Disadvantage: Cannot determine them!

CHOOZ already tried. Limited by systematic uncertainties on reactor flux and cross sections.

How to reduce systematics ?

- **Solution:** Use **2** detectors
- Additional **NEAR** detector: measure flux and cross sections BEFORE oscillations.
- Even better: **interchange** NEAR and FAR detectors part of the time to reduce detector systematics



Technique

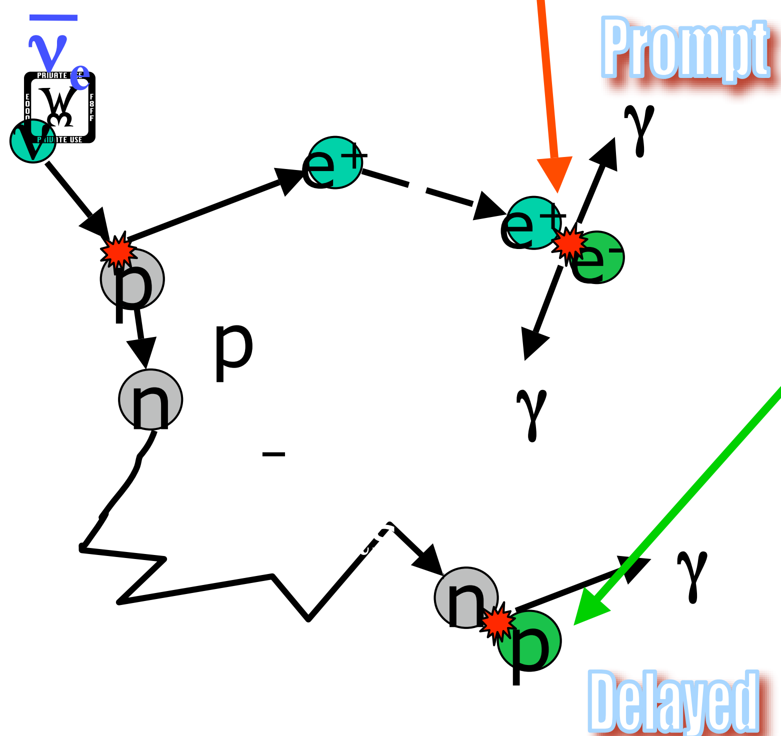
Measure through inverse β decay:

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

e^+ annihilates with e^- of liquid: MeV → 2 photons

- Detector : Liquid scintillator loaded with gadolinium:

  Large cross section for neutron capture → photons

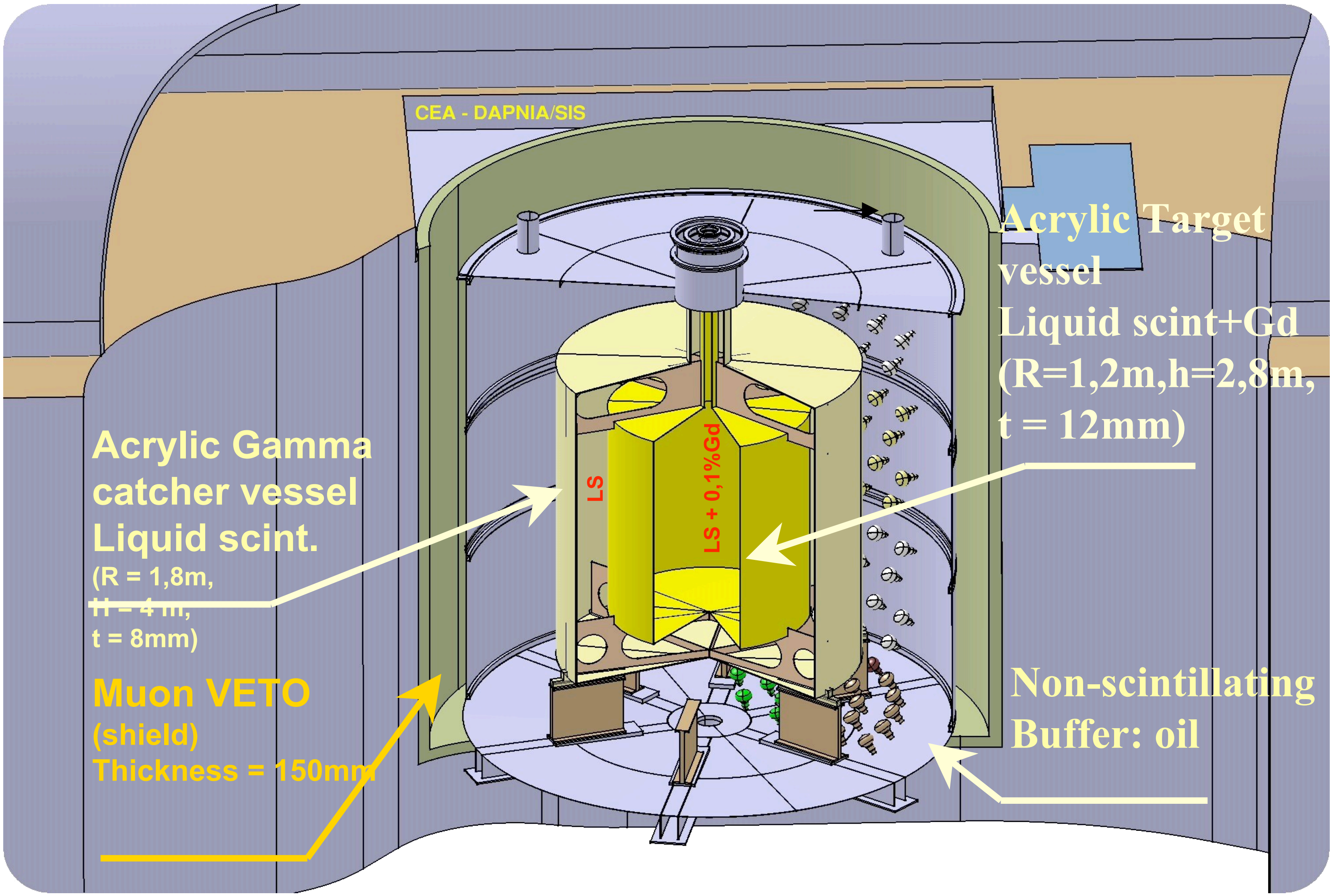


n captured by Gadolinium:
8 MeV of photons emitted within 10's of μsec.

Delayed Coincidence of 2 signals
Reduces background

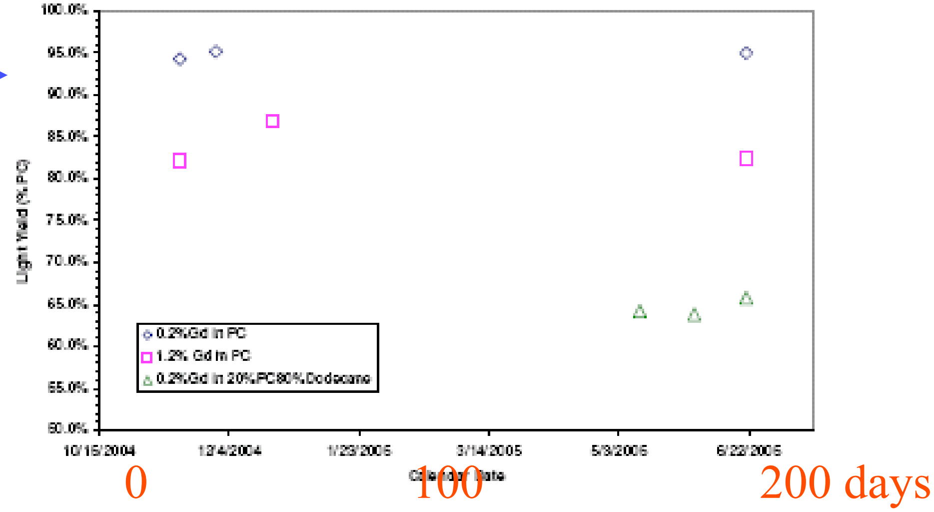
Double Chooz detector

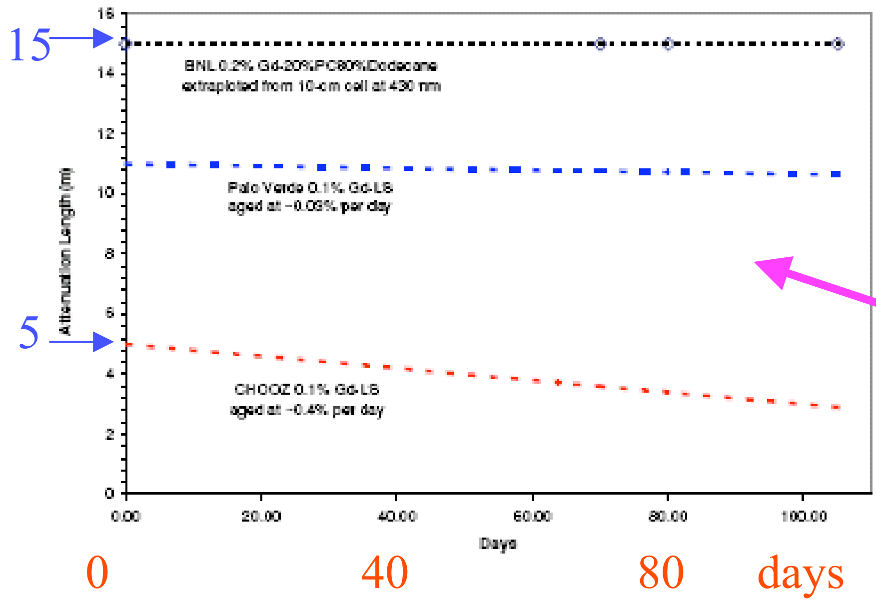
Inner detector, gamma catcher, mineral oil buffer , inner μ , outer veto (scintillator strips)



Scintillator performance: Light yield and absorbance.

Light yield in % of pseudocumene
As measured in BNL samples:
Stable over 220 days.





Comparison of degradation of
Attenuation length over 100 days
For CHOOZ, Palo Verde and BNL.

Must continue checks with final vessel

But there does NOT seem to be any cause for worry.

Reduction of systematics

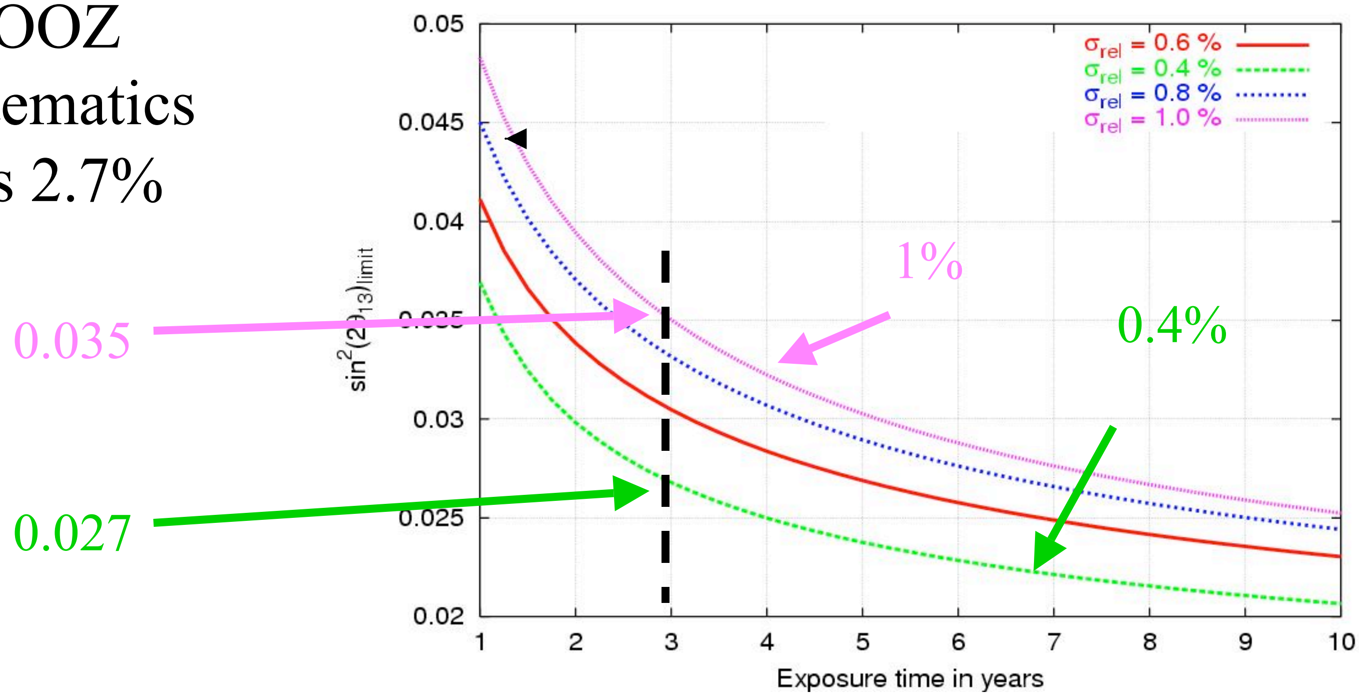
Variable	CHOOZ (%)	Double Chooz (%)
ν flux and σ	1.9	<0.1
Reactor power	0.7	<0.1
Energy per fission	0.6	<0.1
Total	**2.7**	**<0.6**

Importance of systematics

Importance of systematics

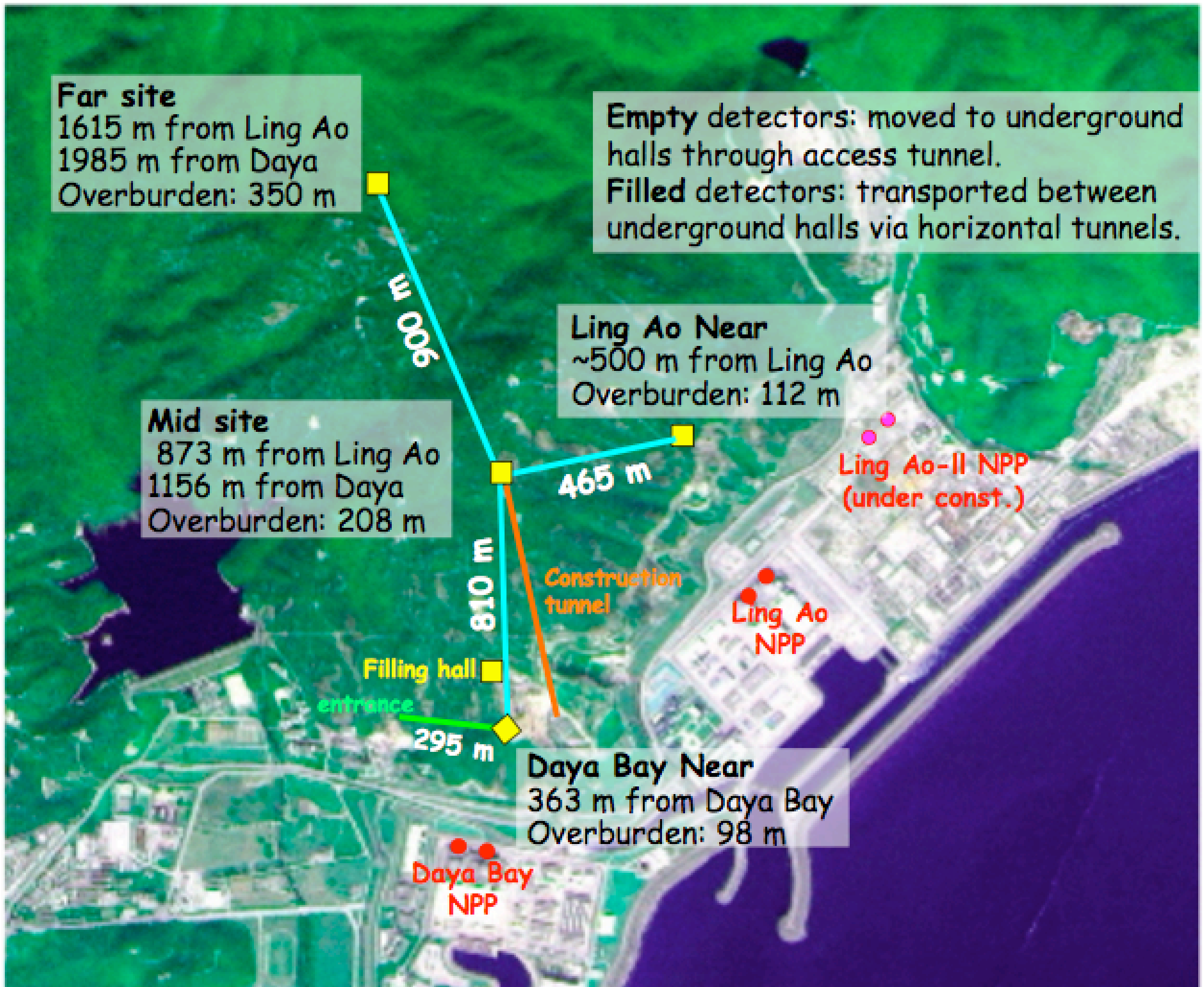
Example:
Double CHOOZ

CHOOZ
systematics
Was 2.7%



Reduction from 1% to 0.4% equivalent to a much longer run

Daya Bay


Far site
1615 m from Ling Ao
1985 m from Daya
Overburden: 350 m
Empty detectors: moved to underground halls through access tunnel.
Filled detectors: transported between underground halls via horizontal tunnels.
900 m
Ling Ao Near
~500 m from Ling Ao
Overburden: 112 m
Mid site
873 m from Ling Ao
1156 m from Daya
Overburden: 208 m
465 m
Ling Ao-II NPP
(under const.)
810 m
Construction tunnel
Ling Ao
NPP
Filling hall
entrance
295 m
Daya Bay Near
363 m from Daya Bay
Overburden: 98 m
Daya Bay
NPP

Proposed experiments

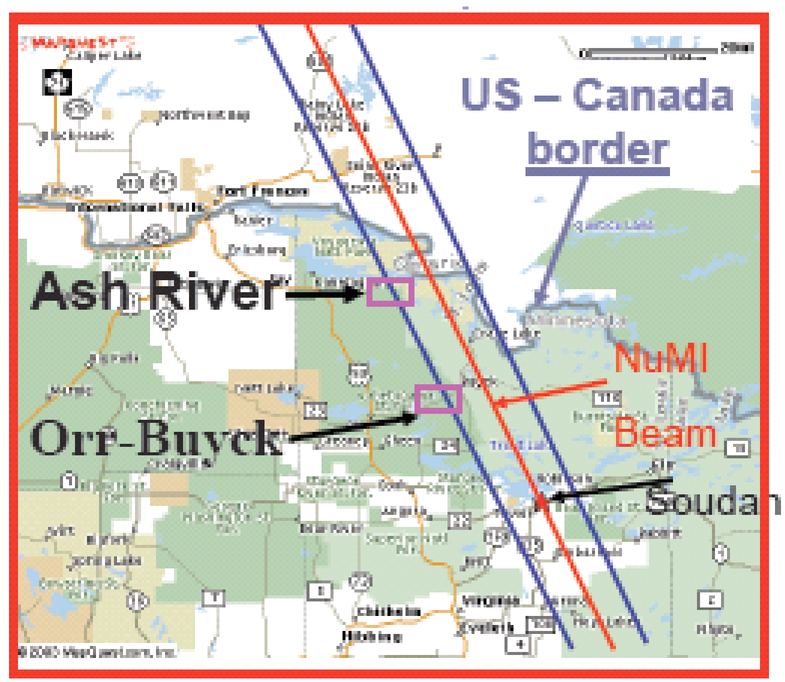
CHOOZ systematics was 2.7%

Experiment	Location	Sites	Systematics	Limit
Double CHOOZ	France	Near/Far	0.6%	**0.03**
Braidwood	USA	Near/Far	0.3%	**0.005**
Daya Bay	China	Near/Mid/Far	0.36-0.12%	**0.009-0.006**

Future (Accelerators)

T2K (Japan) 295km

NOνA (NUMI beam) 810km



Both projects are Long Baseline Off-axis projects.
They search for $\nu_\mu \sim \nu_e$ oscillations by searching for ν_e appearance in a ν_μ beam.
Determine that θ_{13} is non-zero. Measure it?
Mass hierarchy?

$P(\nu_e \text{--->} \nu_\mu)$

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) \;\approx\;& \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
&\pm \sin\delta_{CP}\; \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
&+ \cos\delta_{CP}\alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
&+ \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

Matter Effects

In vacuum and without CP violation:

$$P(\nu_\mu - \nu_e)_{vac} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{atm}$$

with $\Delta_{atm} = 1.27\,\Delta m^2_{32}\,(L/E)$

For $\Delta m^2_{32} = 2.5 \times 10^{-3}\ eV^2$ and for maximum oscillation

We need: $\Delta_{atm} = \pi/2 \rightarrow L(km)/E(GeV) = 495$

For L = 800km E must be 1.64 GeV, and for L = 295km E = 0.6 GeV

Introducing matter effects, at the first oscillation maximum:

$$P(\nu_\mu - \nu_e)_{mat} = [1 +- (2E/E_R)]\,P(\nu_\mu - \nu_e)_{vac}$$

with $E_R = [12\ GeV][\Delta m^2_{32}/(2.5\times10^{-3})][2.8\ gm.cm^{-3}/\rho] \sim 12\ GeV$

+- depends on the mass hierarchy.

Matter effects grow with energy and therefore with distance.

3 times larger (27%) at NOνA (1.64 GeV) than at T2K (0.6 GeV)

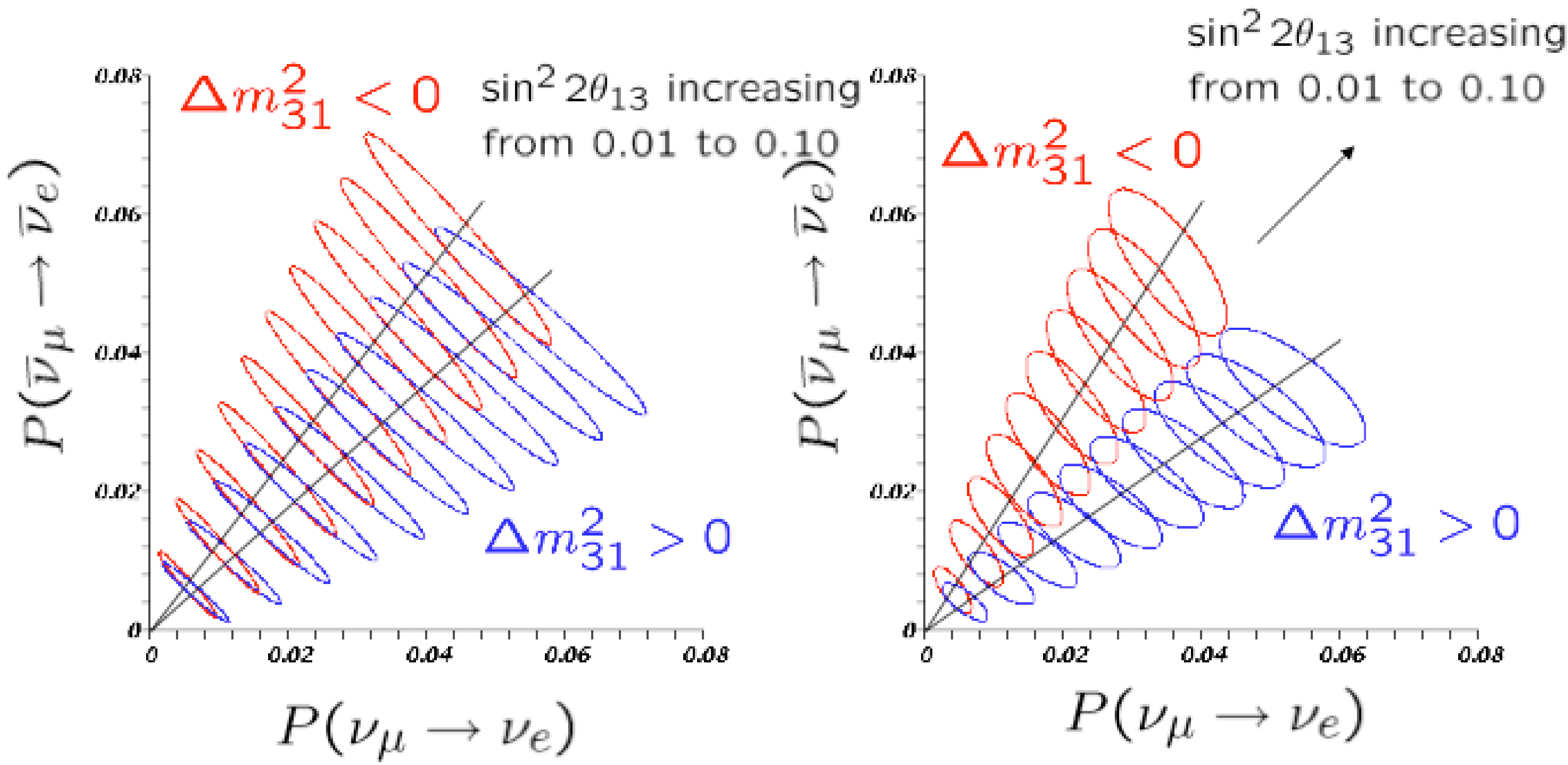
T2K-NOvA Comparison

E_ν=0.6 GeV, L=295 km

T2K Parameters

E_ν=2.3 GeV, L=810 km

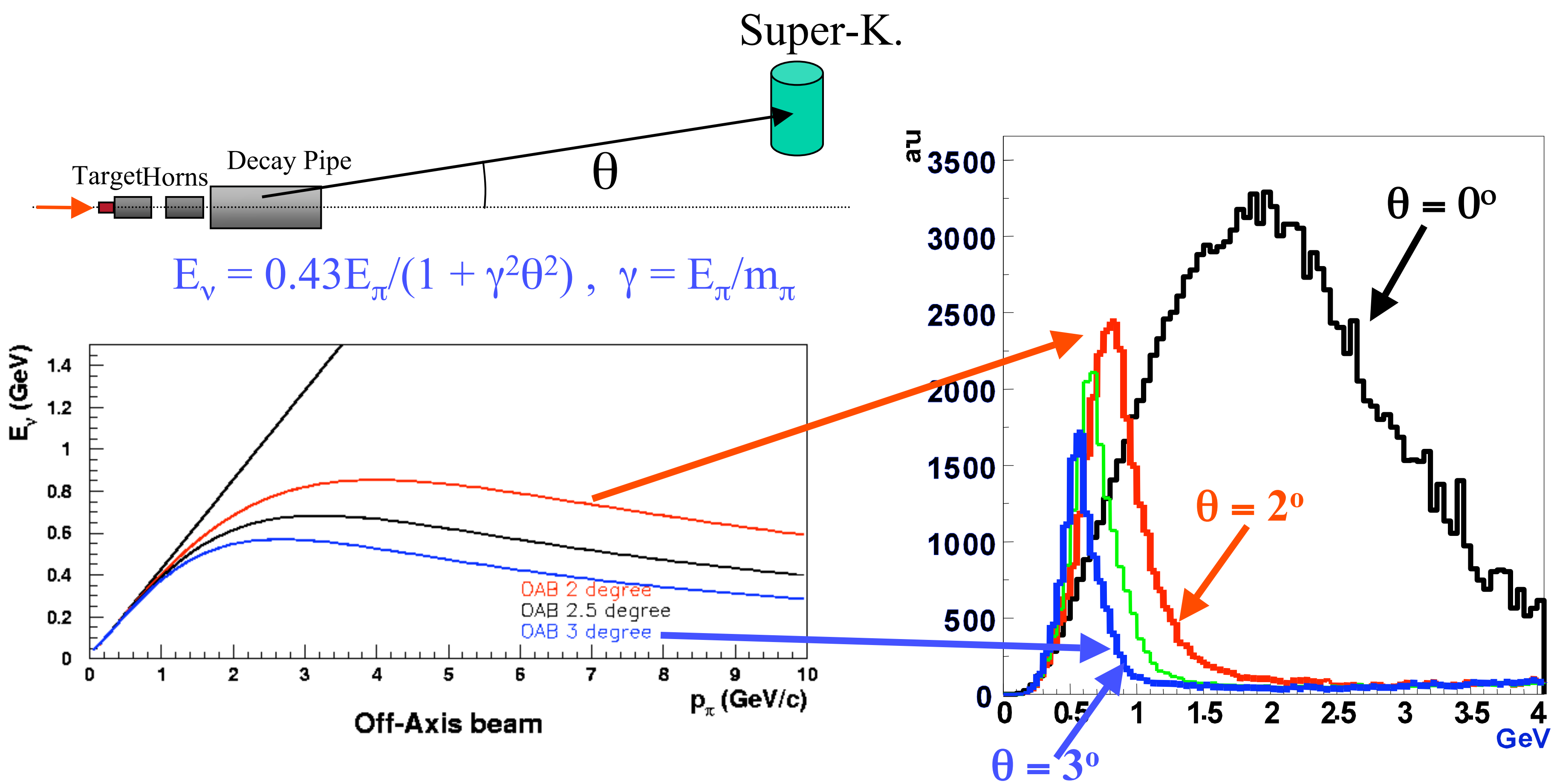
NOvA Parameters



- **Hierarchy has bigger effect in NOvA, because of increased matter effects at higher energy and distance.**

OFF-AXIS Technique

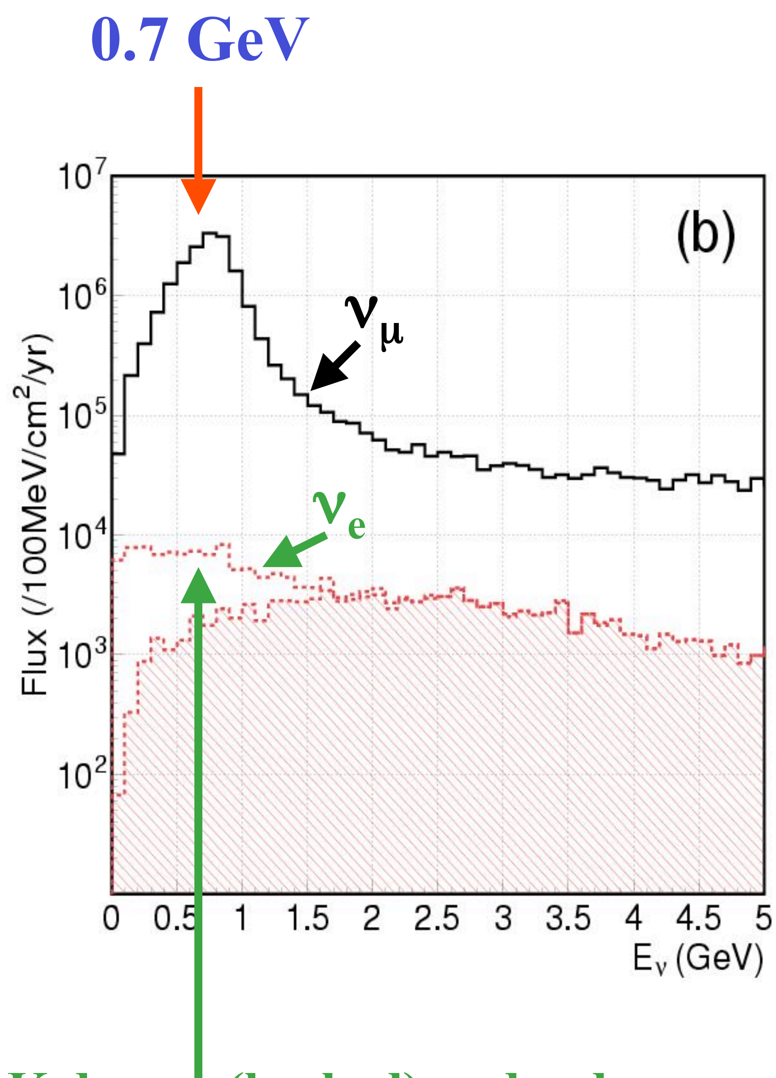
Most decay pions give similar neutrino energies at the detector:
The Neutrino Energy Spectrum is narrow: know where to expect ν_e appearance
Can choose the off-axis angle and select the mean energy of the beam.
(Optimizes the oscillation probability)



$$E_\nu = 0.43E_\pi/(1+\gamma^2\theta^2)\ ,\ \ \gamma = E_\pi/m_\pi$$

T2K

- New 40 GeV Proton Synchrotron (JPARC)
- Reconstructed Super-K
- Near detector to measure unoscillated flux distance of 280 m (Maybe 2km also)
- JPARC ready in 2008
- T2K construction 2004-2008
- Data-taking starting in 2009

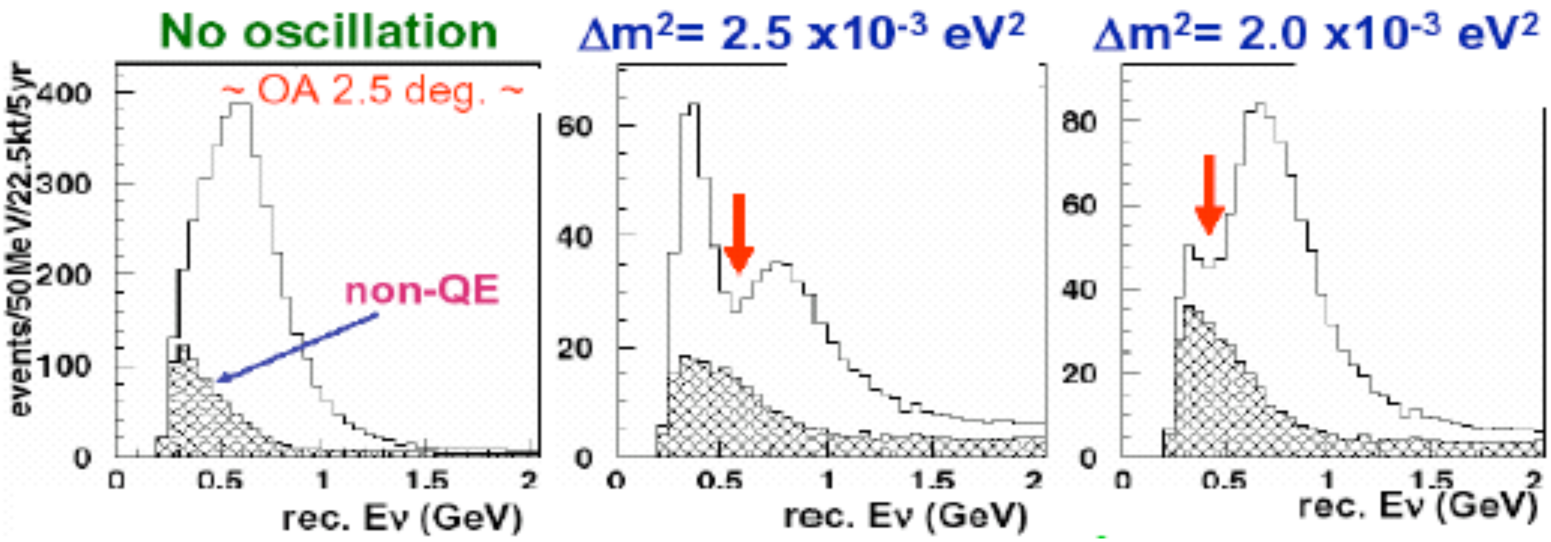


ν_e from K decays (hashed) and μ decays

0.4 % background at peak

Irreducible background to a **$\nu_\mu \rightarrow \nu_e$ search.**

ν_μ disappearance: Δm_{23}^2 and θ_{23}.



Position of dip

↓

Δm_{23}^2 to an accuracy of ~ 10^{-4} eV^2

Depth of dip

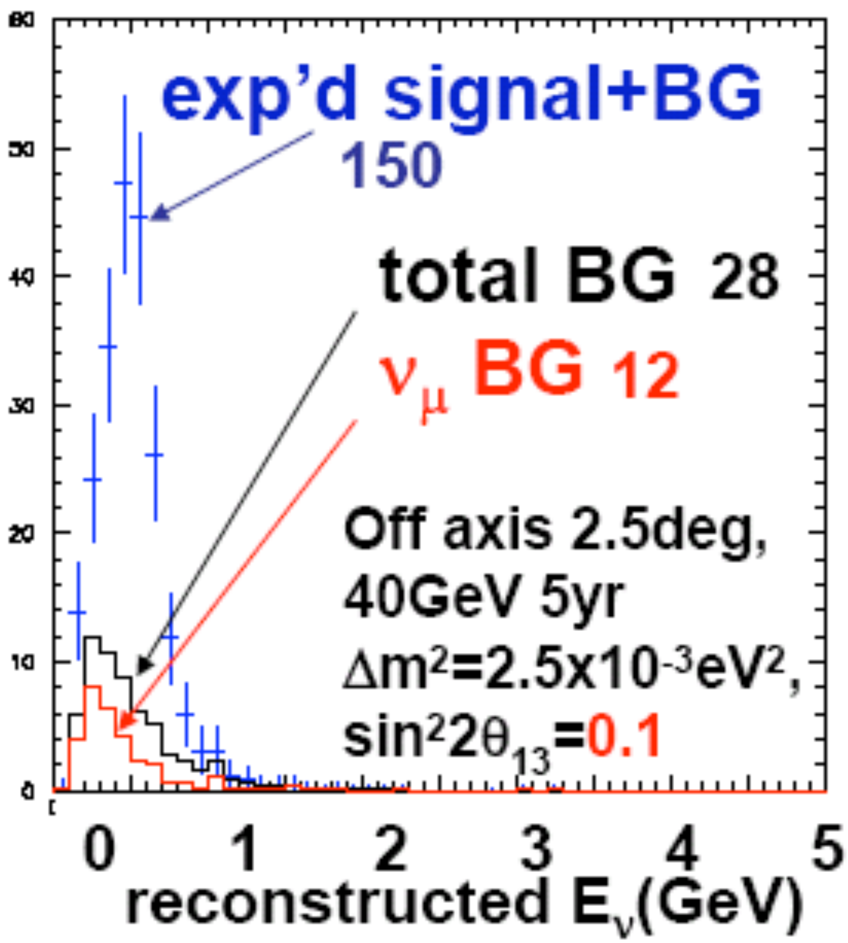
↓

$\sin^2 2\theta_{23}$ to an accuracy of 0.01

Factor of 10 improvement in both

Measurement of $\theta_{13.}$

ν_e appearance



Sensitivity, correlations, degeneracies

Limit on $\sin^2 2\theta_{13}$ if we take into account correlations and degeneracies

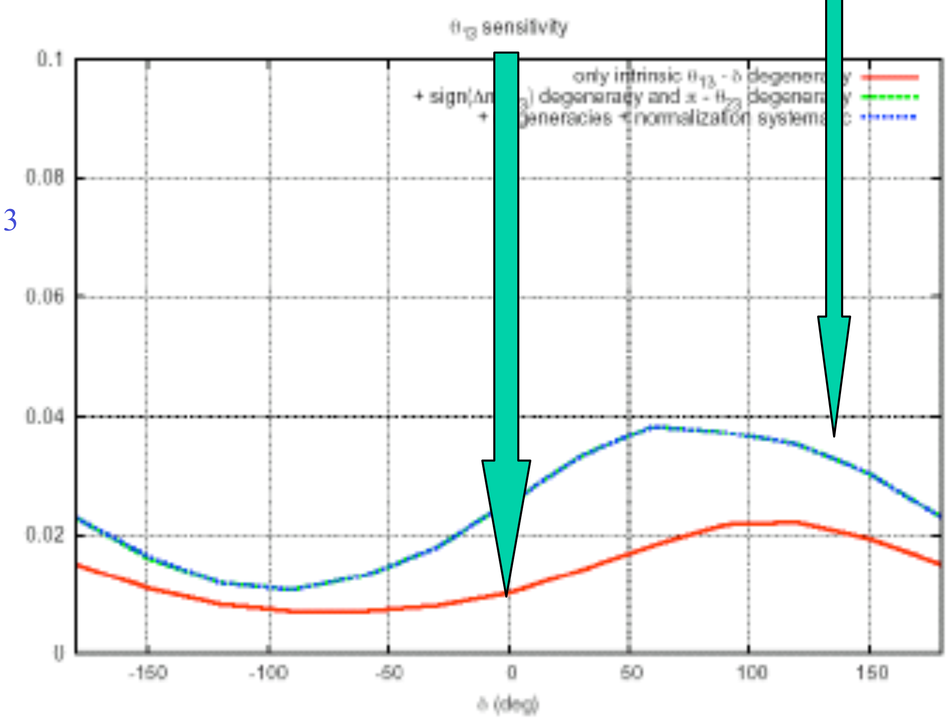
Limit without taking into account degeneracies

0.1

$\text{Sin}^2\, 2\theta_{13}$

0.05

0.0

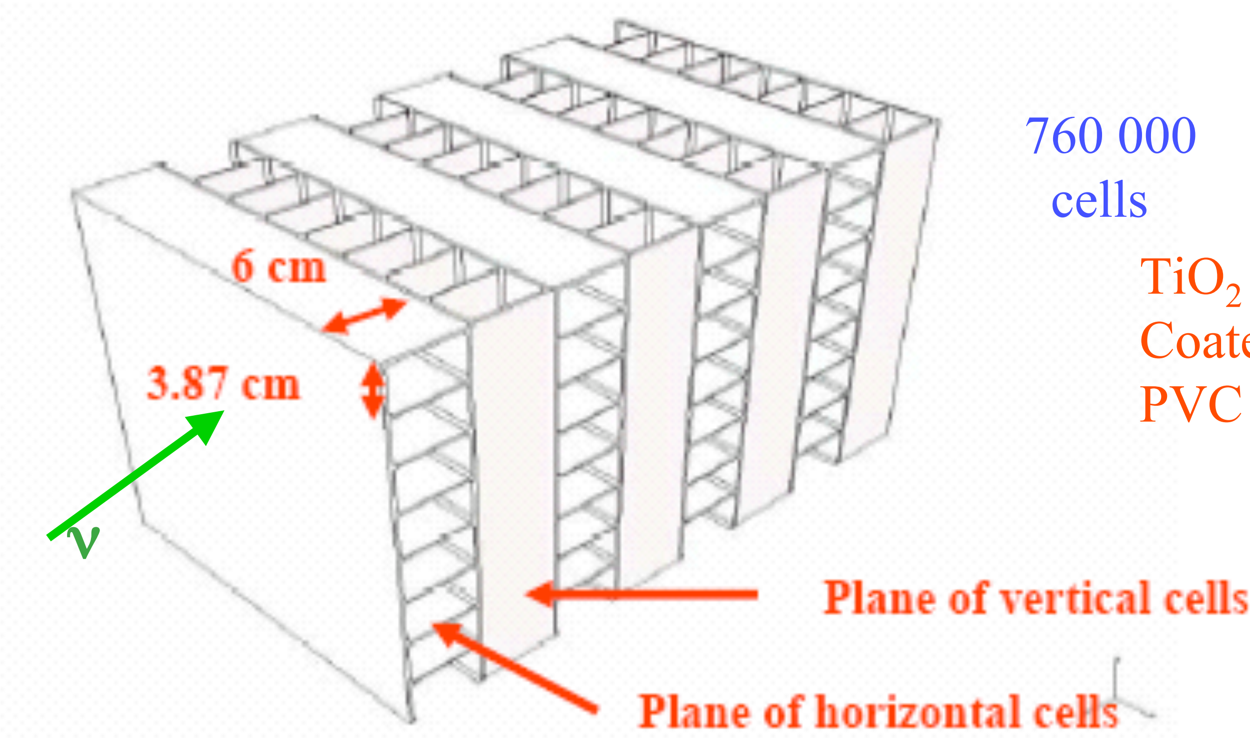


–150 **0** **δ_{CP}** 150

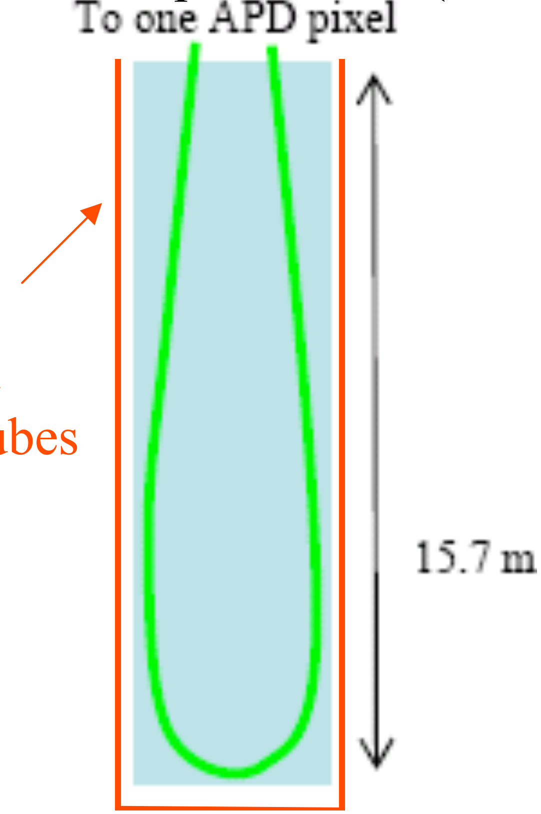
$\text{Sin}^2\, 2\theta_{13} \sim 0.01 - 0.04$

NOνA Detector

Given relatively high energy of NUMI beam,
decided to optimize NOνA for resolution of the mass hierarchy
Detector placed 14 mrad (12 km) Off-axis of the Fermilab NUMI beam (MINOS).
At Ash River near Canadian border (L = 810km) : New site. Above ground.
Fully active detector consisting of 15.7m long plastic cells filled with liquid scintillator: Total mass 30 ktons.
Each cell viewed by a looped WLS fibre read by an avalanche photodiode (APD)

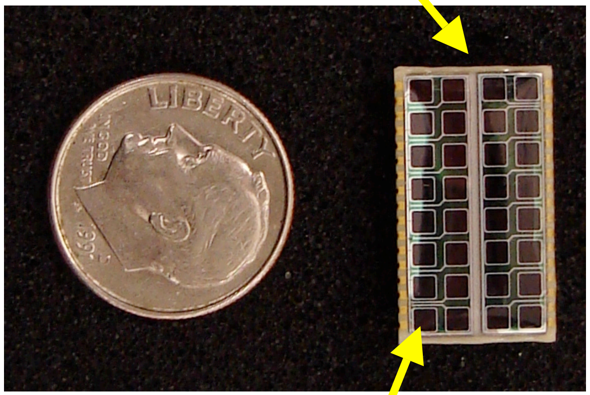


760 000
cells



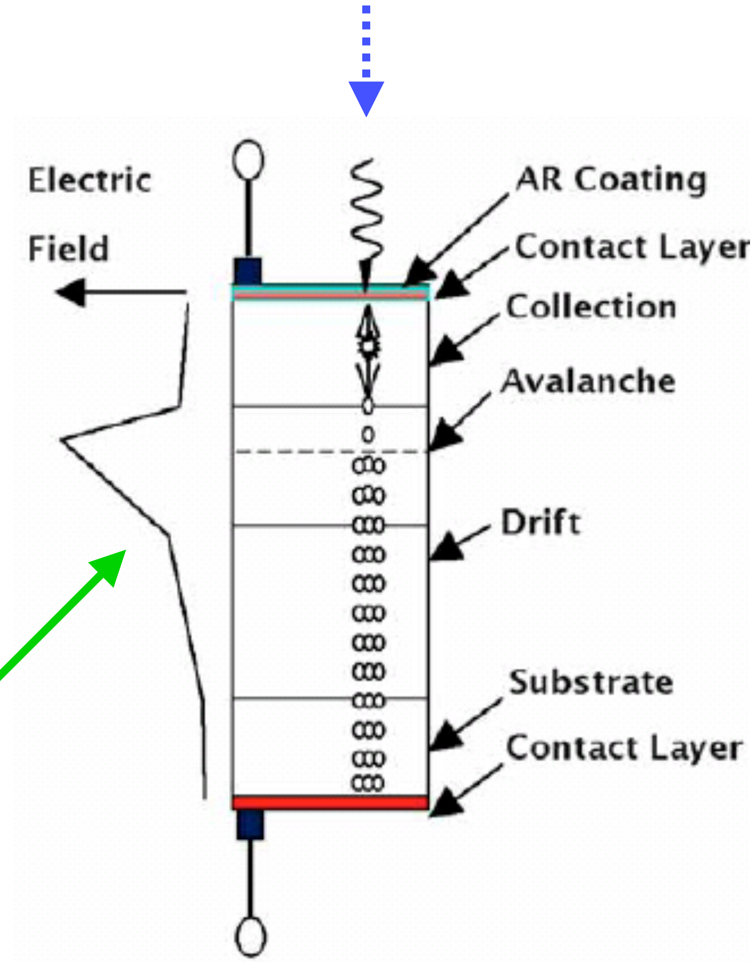
Avalanche Photodiode

- Hamamatsu 32 APD arrays



- Pixel size 1.8mm x 1.05mm
  (Fibre 0.8mm diameter)
- Operating voltage 400 Volts
- Gain 100
- Needs amplifier (PMT usually 10^6)
- Operating temperature: -15º C
  (reduces noise)

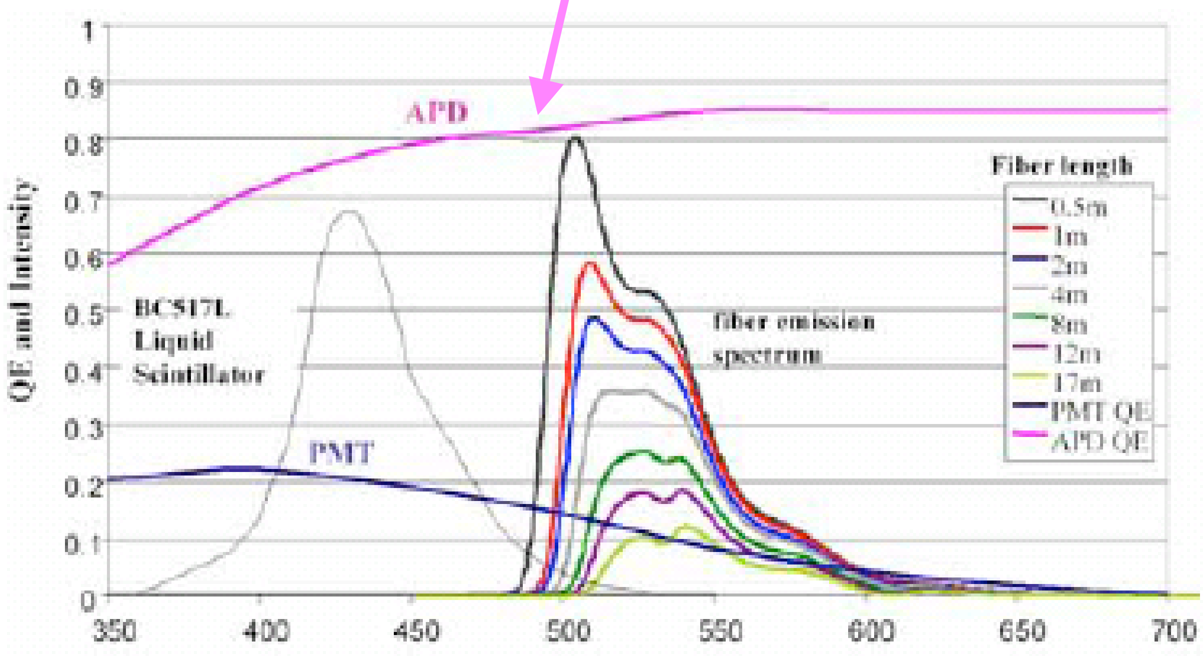
Photon



Asic for APD’s: 2.5 pe noise
→ S/N ~ 30/2.5 = 12

NOνA

The quantum efficiency of APD's is much higher than a pm's: **~85%** . Especially at the higher wave lengths surviving after traversing the fibre.



Asic for APD's: 2.5 pe noise
→ **S/N ~ 12**

The Beam

PROTONS: 6.5 x 10^{20} protons on target per year.

Greatly helped by

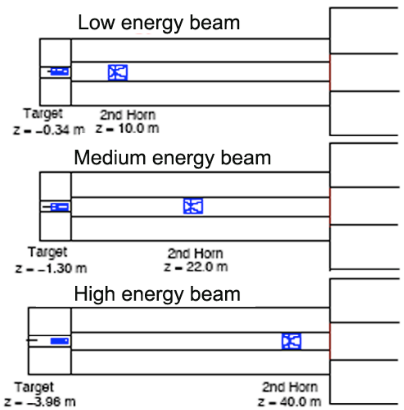
- Termination of Collider programme by 2009.

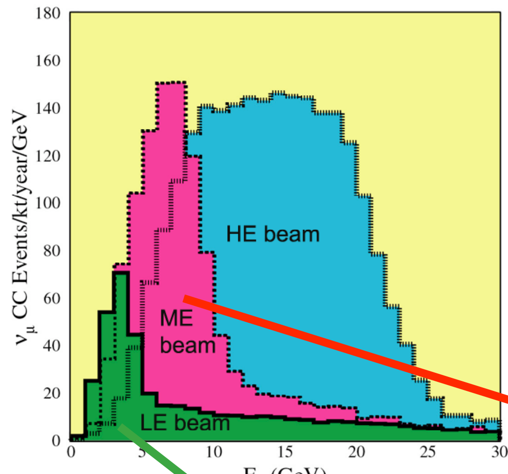
A gain of a factor of > 2 in numbers of protons delivered.
As of today, this extrapolates to: **4.8 x 10^{20}**

Longer term: Construction of an 8 GeV proton driver: x 4

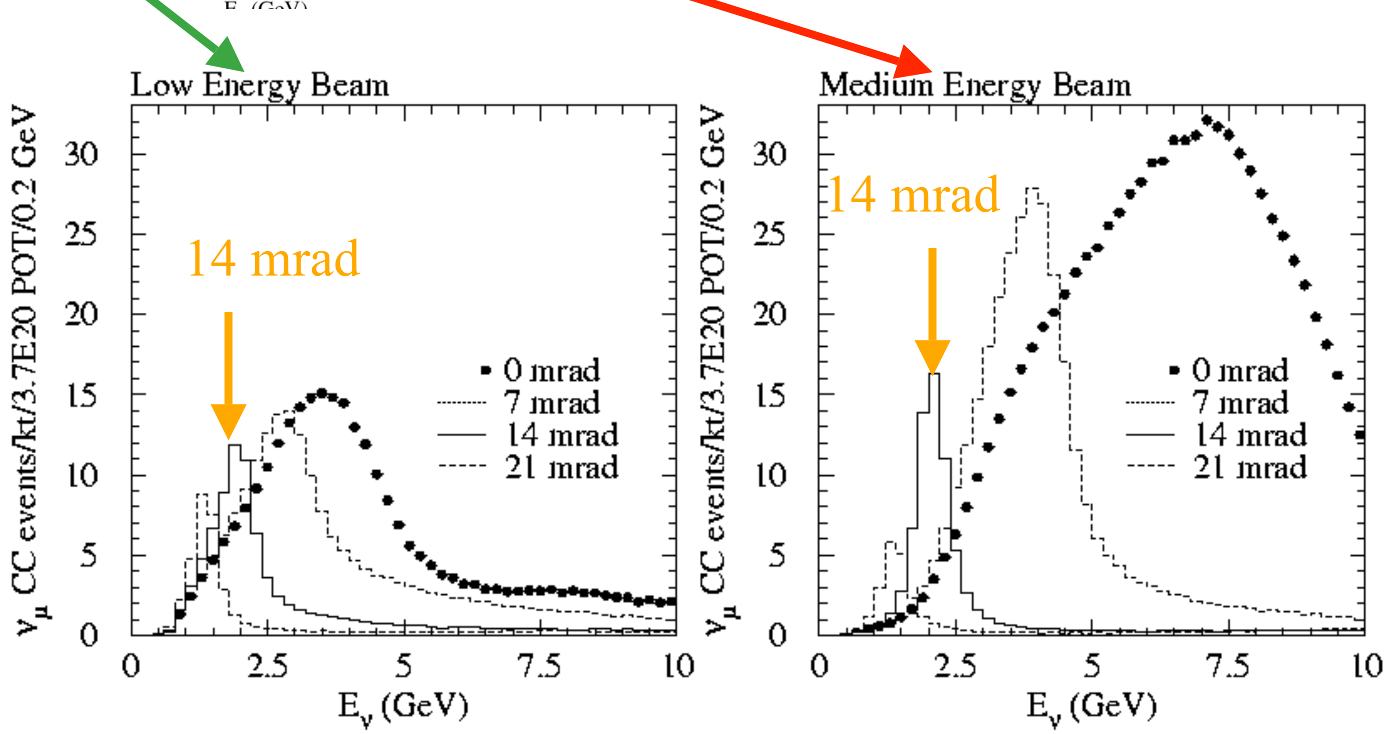
25.2 x 10^{20} protons on target per year is the goal.

The Beam: Same NUMI beam as MINOS

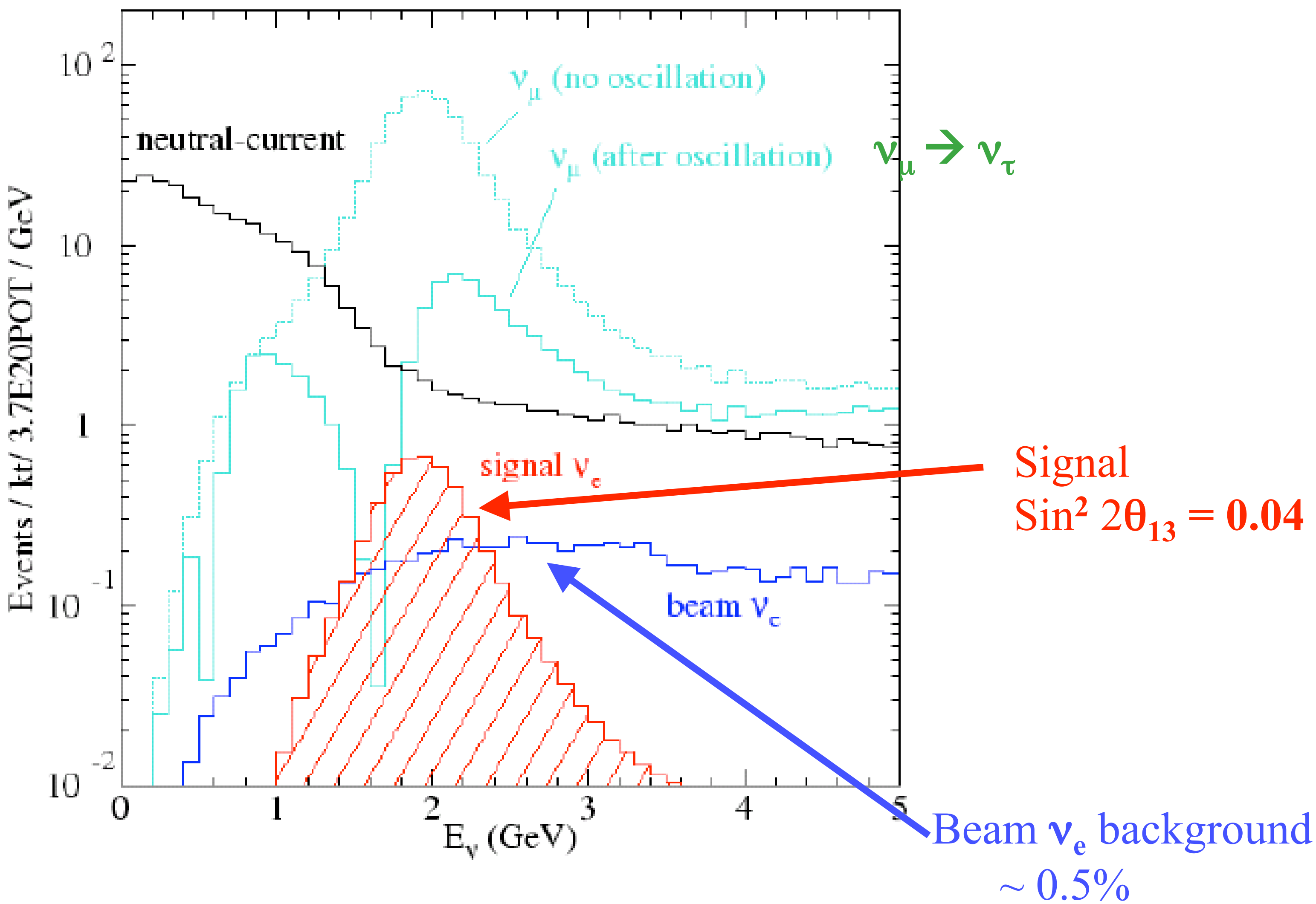




Can select low, medium and high energy beams by moving horn and target
Best is the Medium energy beam



Beam spectra

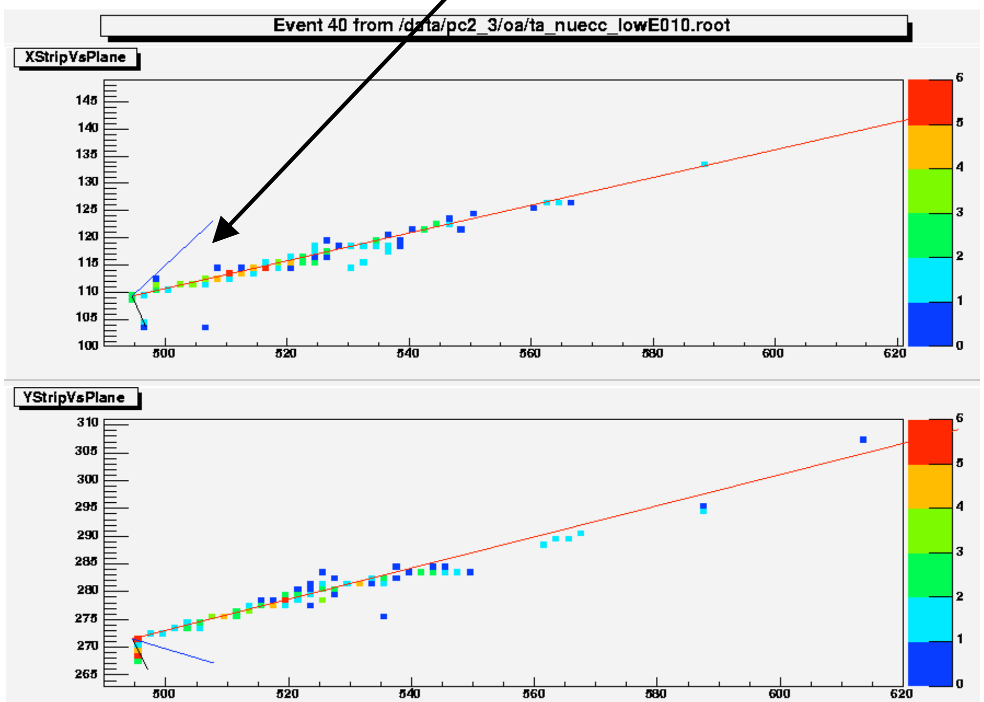


Typical events (Monte Carlo)

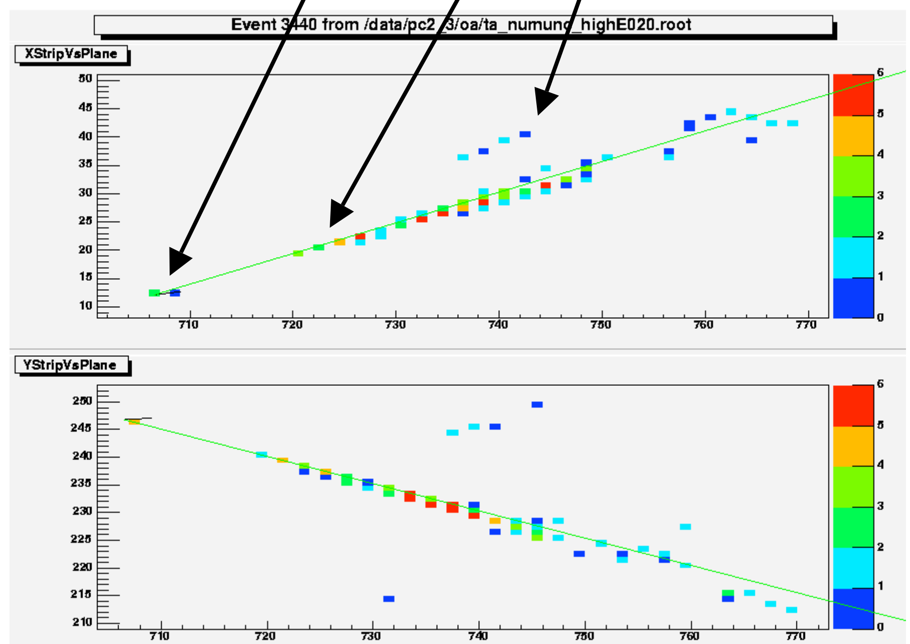
Electron: Shower attached to vertex

π^o --> $\gamma\gamma$: Vertex separated from shower

Second shower

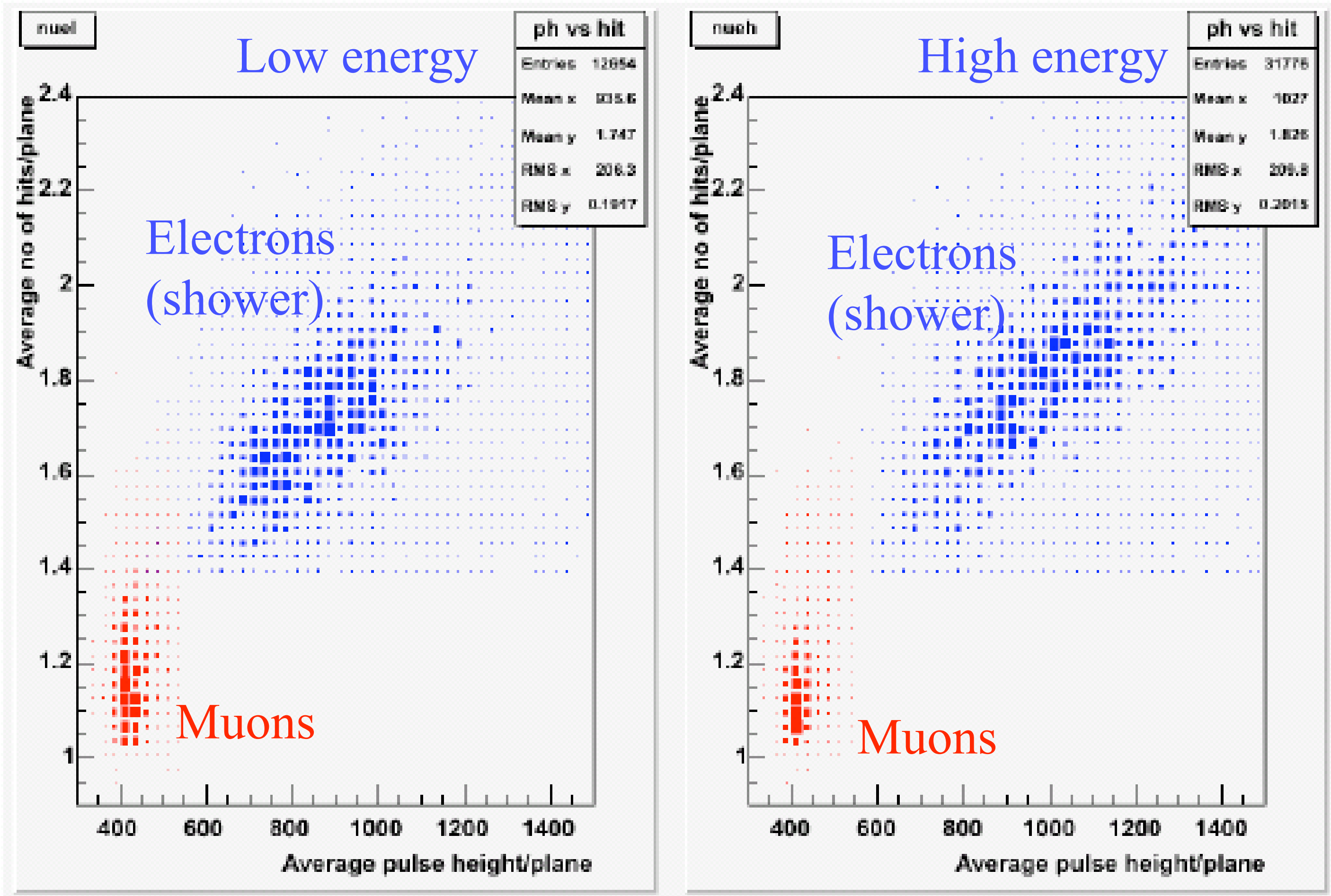


$\nu_e p \rightarrow e^- p \pi^+$



$\nu_\mu N \rightarrow \nu_\mu p \pi^o$

$\nu_\mu - \nu_e$ separation



π^o **in NC** also a problem.

Signal ν_e efficiency: 24%.

ν_μ CC background 4×10^{-4}

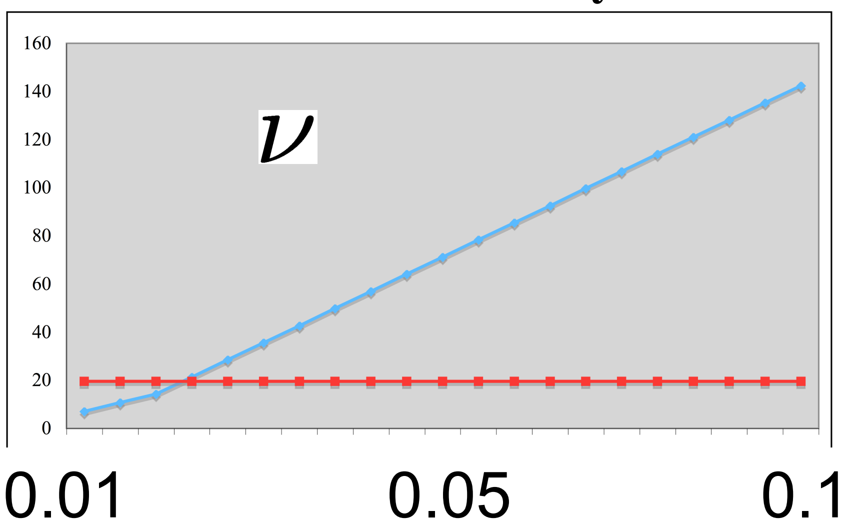
ν_μ NC background 2×10^{-3}

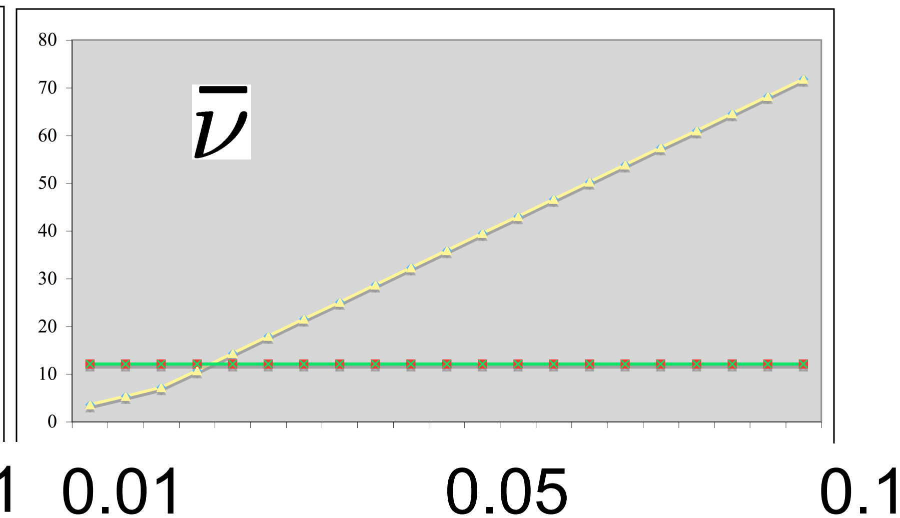
Summary of backgrounds

Background	Events	% Error	Error
Beam $\boldsymbol{\nu}_e$	11.9	7%	0.8
$\mathbf{N}_\mu$ CC	0.5	15%	0.08
NC	7.1	5%	0.4
Total	19.5	5%	0.9

Signal and Backgrounds

- **Statistical Power: why this is hard and we need protons**





For $\sin^2 2\theta_{13} = 0.1$:

ν: S=142.1, B=19.5

$\bar{\nu}$: S= 71.8, B=12.1

5 yrs at 6.5E20 pot/yr, efficiencies included

θ_{23} ambiguity determination

Appearance: Accelerators

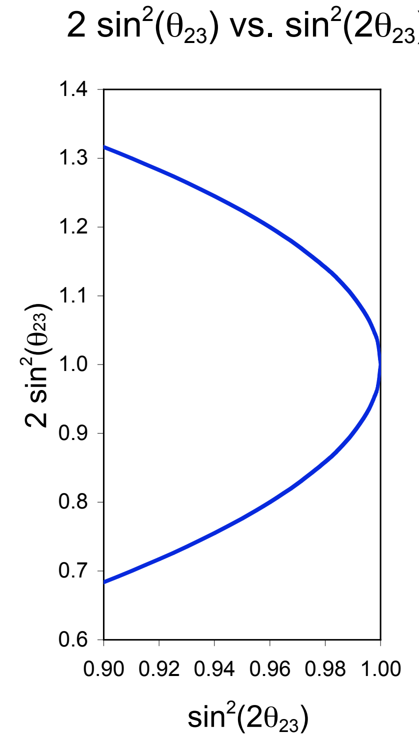
$P(\nu_\mu - \nu_e)_{vac} = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 [(\Delta m_{23}{}^2 L)/(4E_\nu)]$

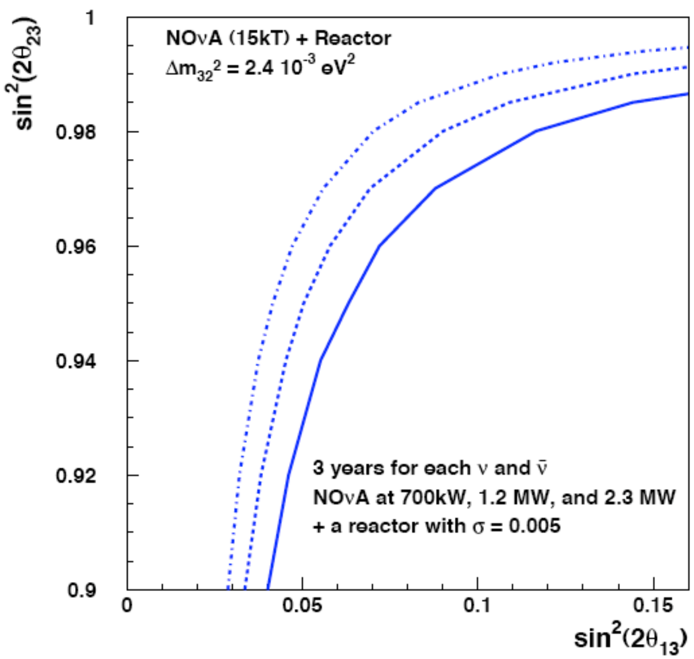
Disappearance: Reactors

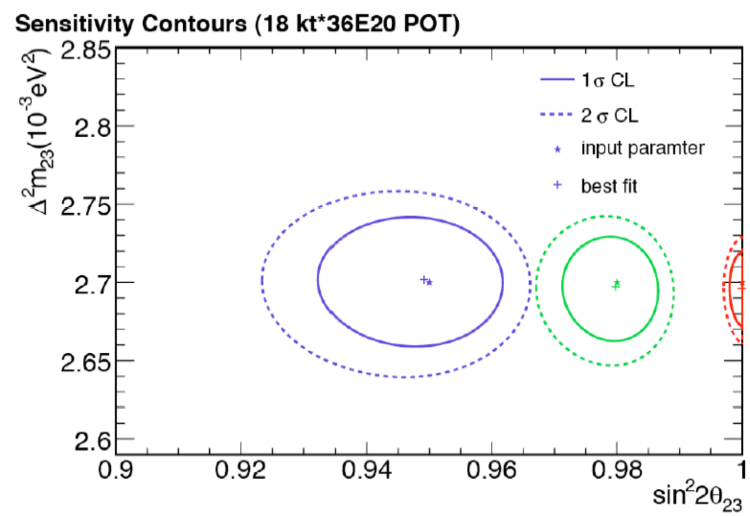
$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2 [(\Delta m_{23}{}^2 L)/(4E_\nu)]$

Combining results can determine θ_{23}

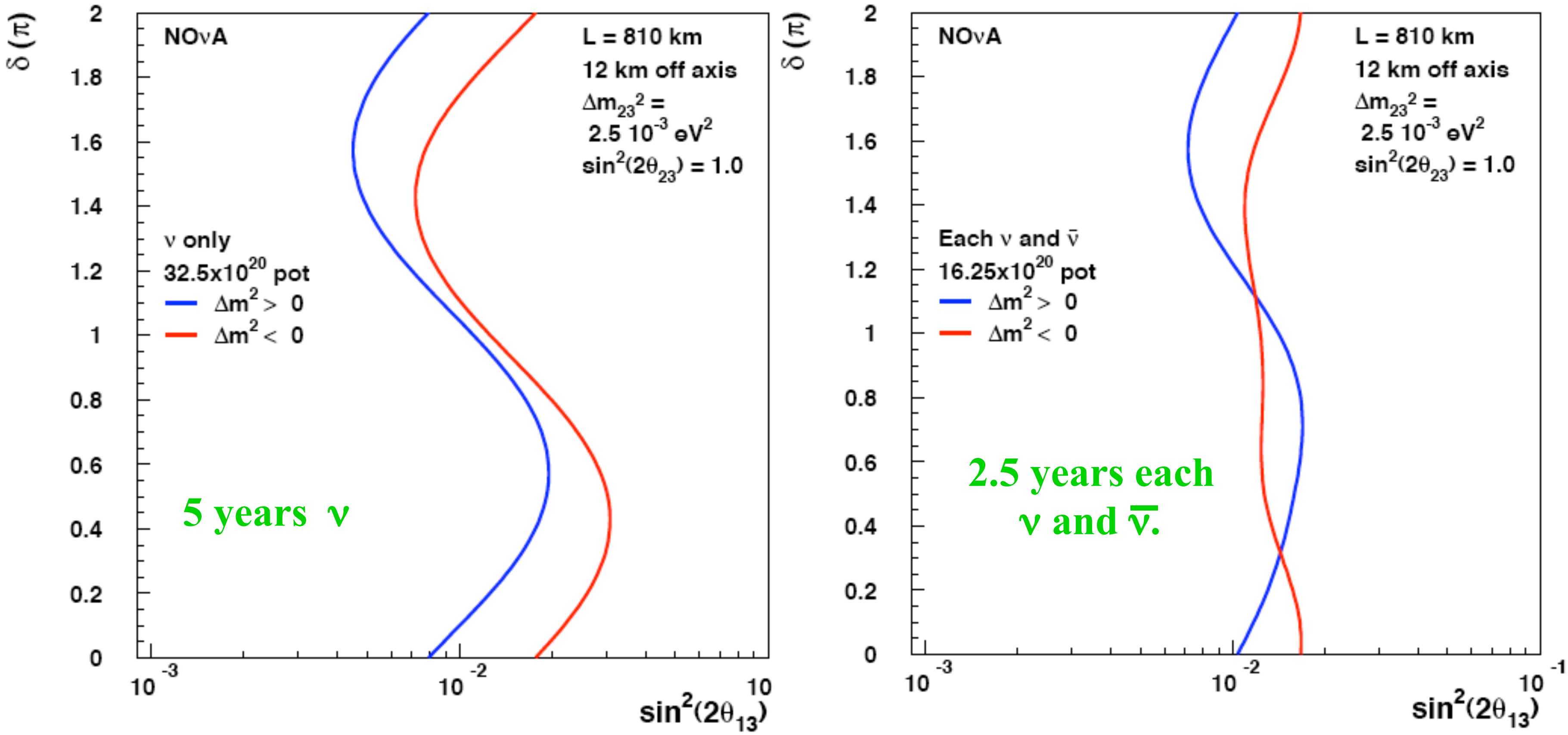
$\sin^2 2\theta_{23}$, say 0.92, $2\theta_{23}$ is 67° or 113 ° and θ_{23} is 33.5° or 56.5





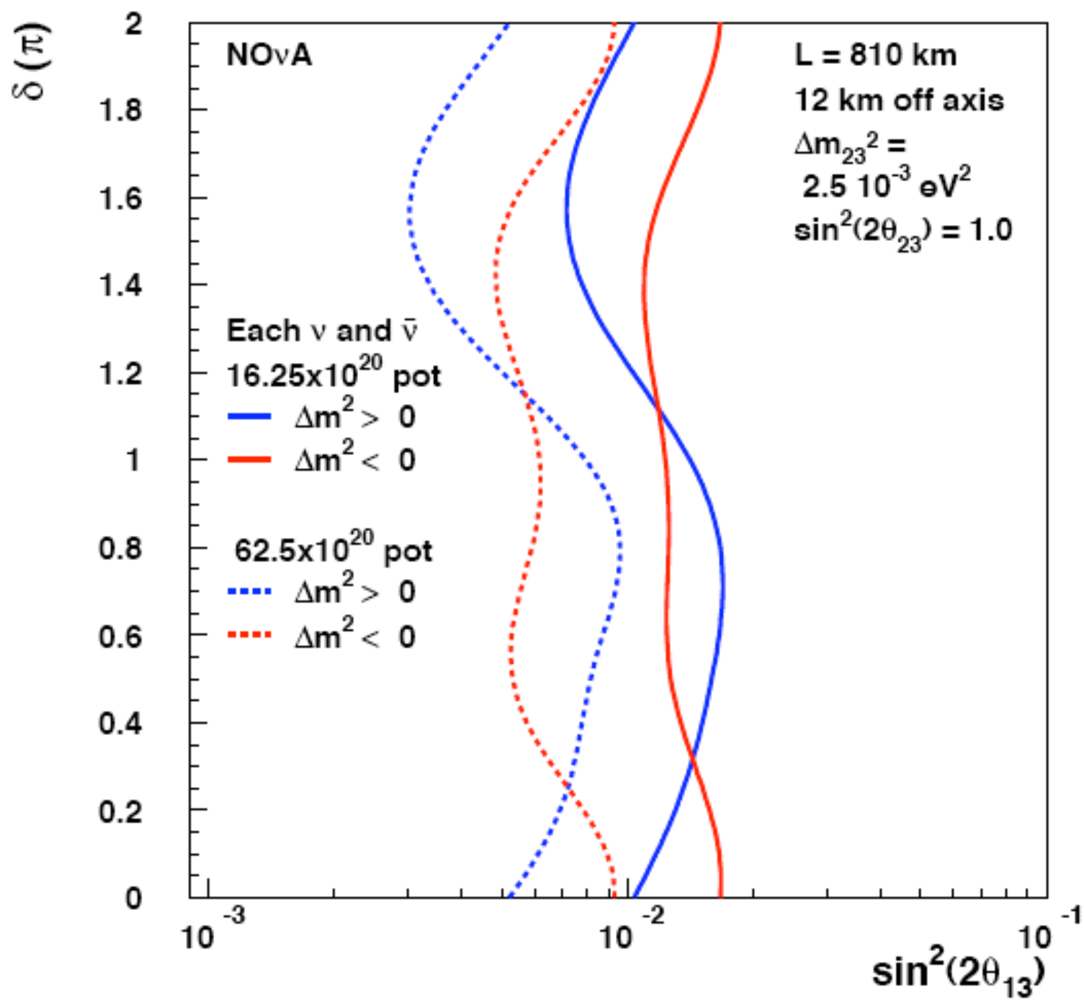


3 σ discovery limits for $\theta_{13} \neq 0$



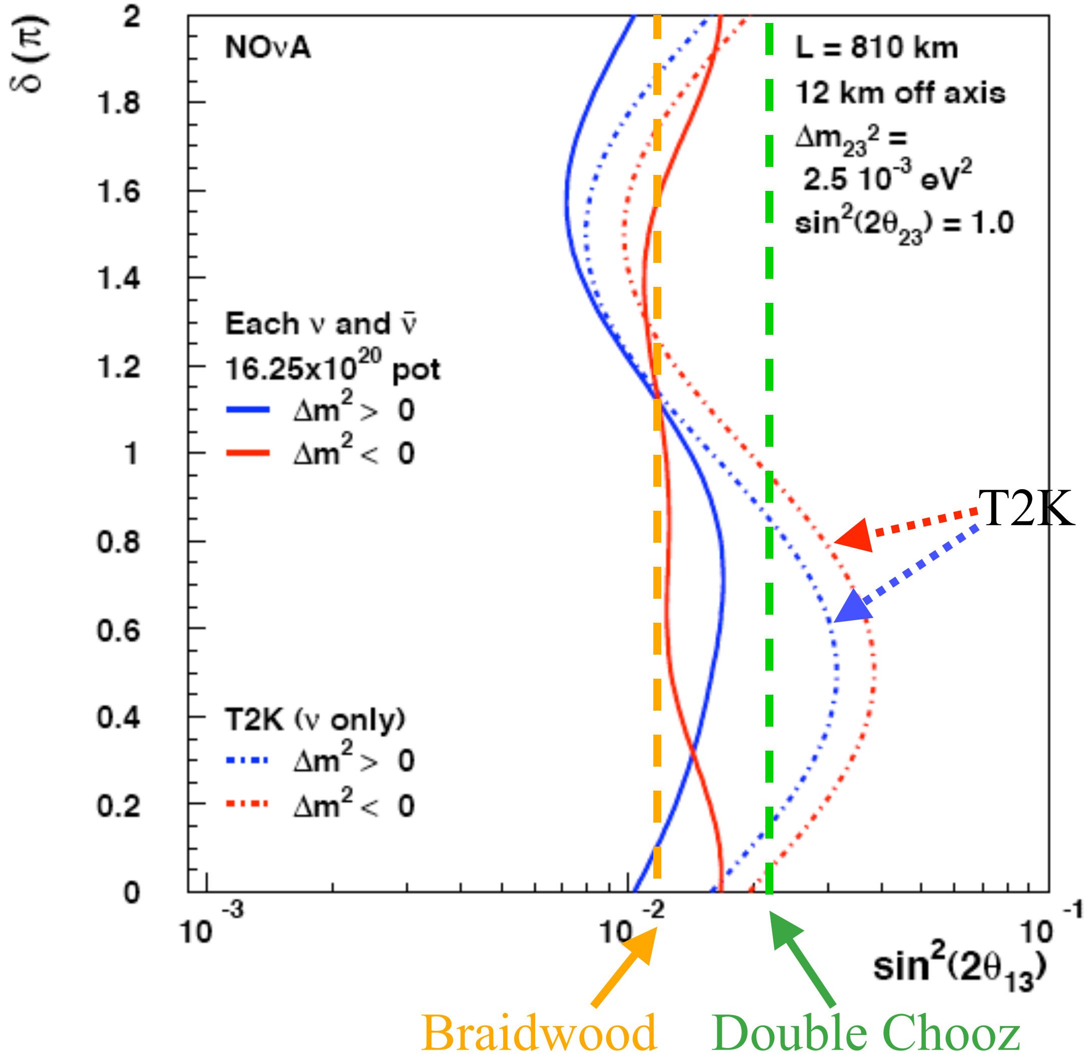
Discovery limit is better than 0.02 for ALL δ's and BOTH mass hierarchies.

3 σ discovery limits for $\theta_{13} \neq 0$
Comparison with Proton Driver

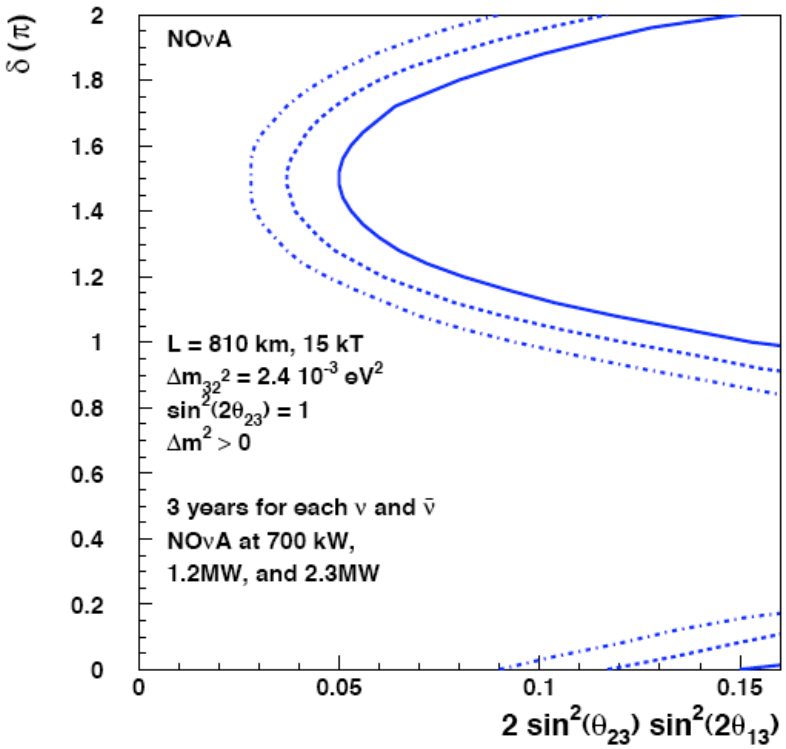


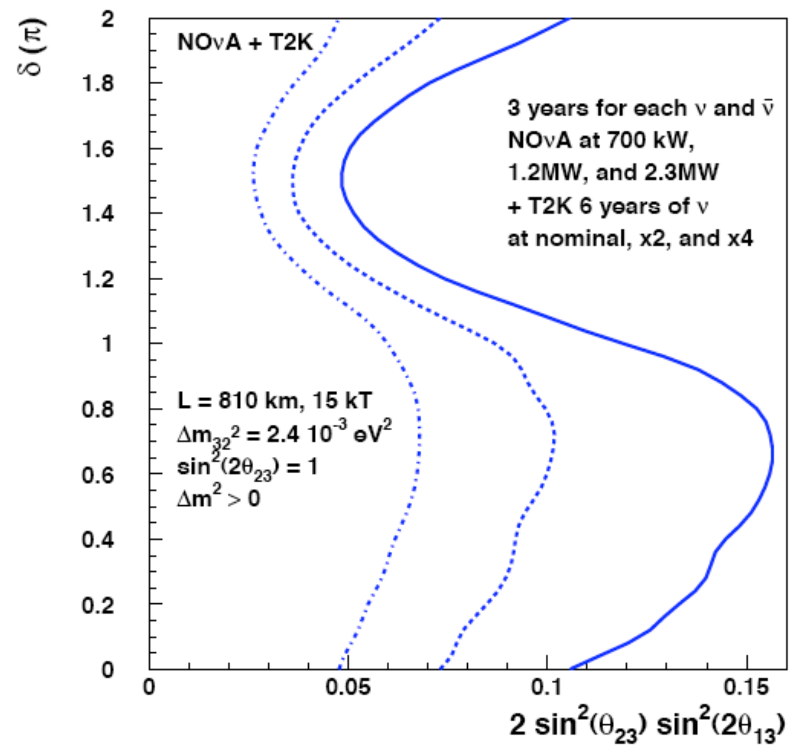
2.5 years each ν and $\bar{\nu}$.

3 σ discovery limits for $\theta_{13} = 0$
Comparison with T2K and 2 Reactor experiments

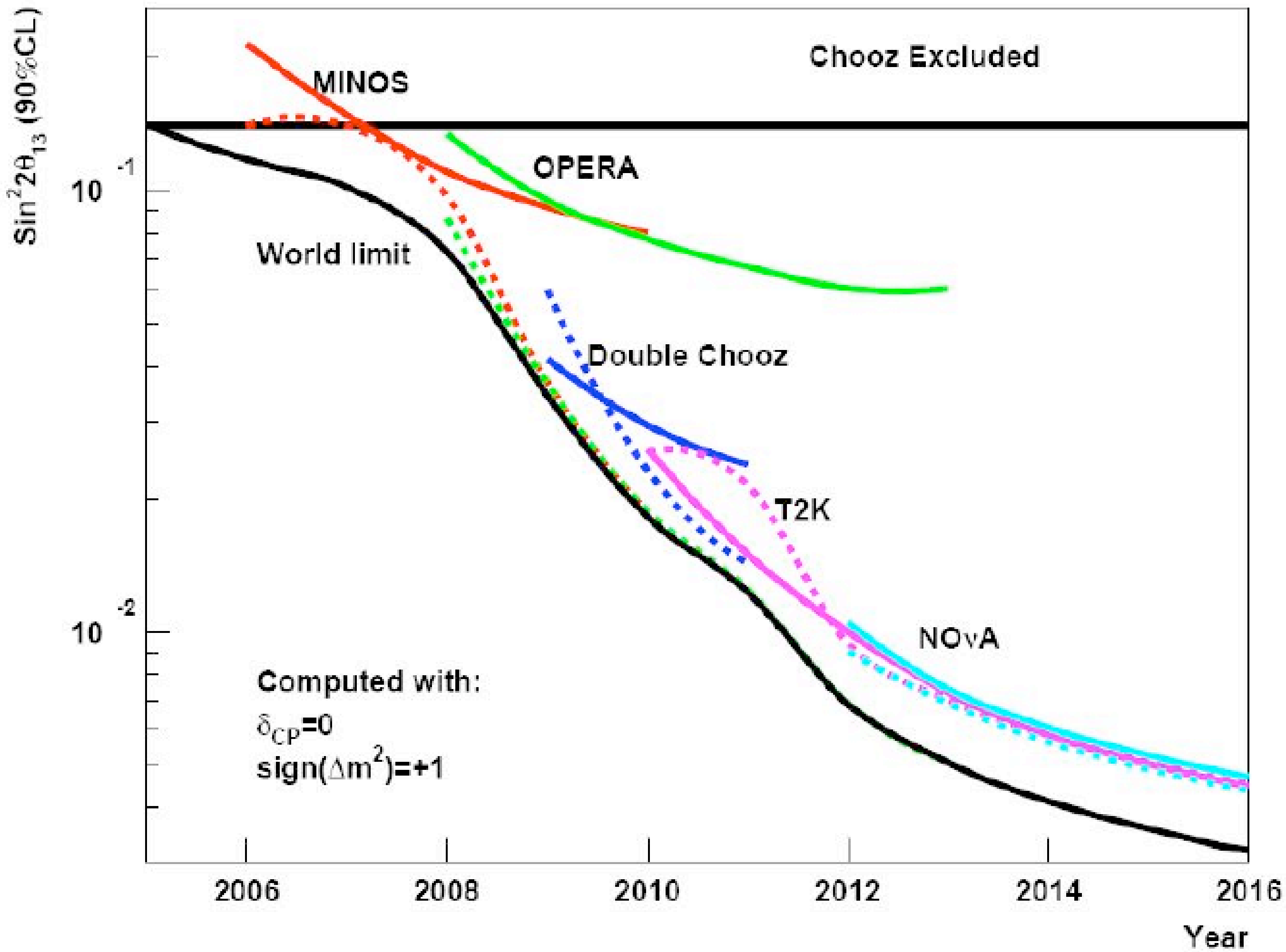


Resolution of mass hierarchy





The road ahead



Mass hierarchy with reactors ?

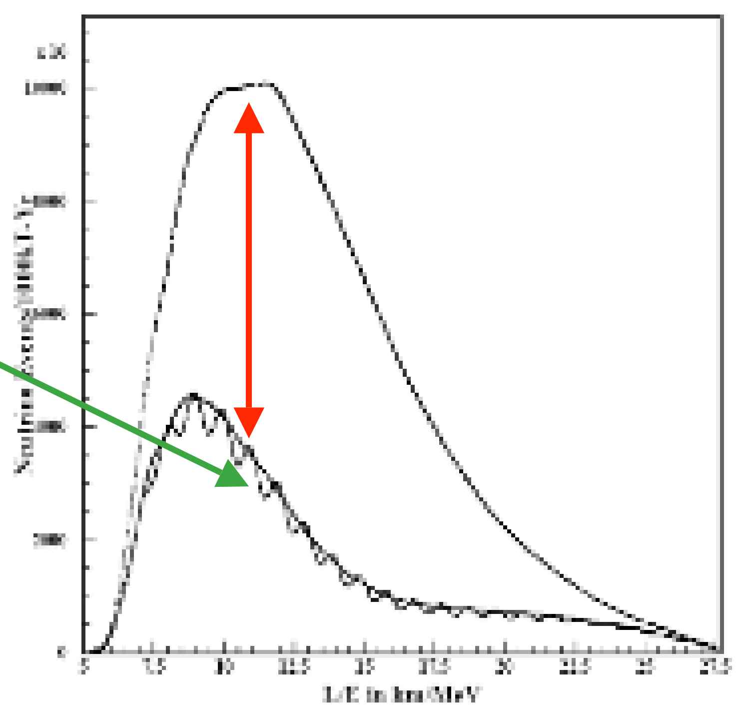
- $P(\nu_e \rightarrow \nu_x) =$

$$1 - \sin^2 2\theta_{12}\, c_{13}^4 \sin^2\Delta_{21} - \sin^2 2\theta_{13}\, c_{12}^2 \sin^2 \Delta_{31} - \sin^2 2\theta_{13}\, s_{12}^2 \sin^2 \Delta_{32}$$

The disappearance formula has 3 terms, each depending on a different Δ.
If we can measure energy with enough precision we should be able to disentangle the 3
For reactors antineutrinos the first term gives the biggest suppression because it is NOT
A function of $\sin^2 2\theta_{13}$.
The other 2 terms give smaller and higher frequency oscillations

In order to enhance the effect of Δ_{31} and Δ_{32},
We should chose L = 56 km such that $\Delta_{21} = \pi/2$
Then we have two other oscillations,
with amplitudes
proportional to the factors
in the Δ_{31} and Δ_{32} terms.

The Δ_{31} term is proportional to $c_{12}^2 = 0.72$
The Δ_{32} term is proportional to $s_{12}^2 = 0.28$
A ratio of 2.57



Mass hierarchy with reactors

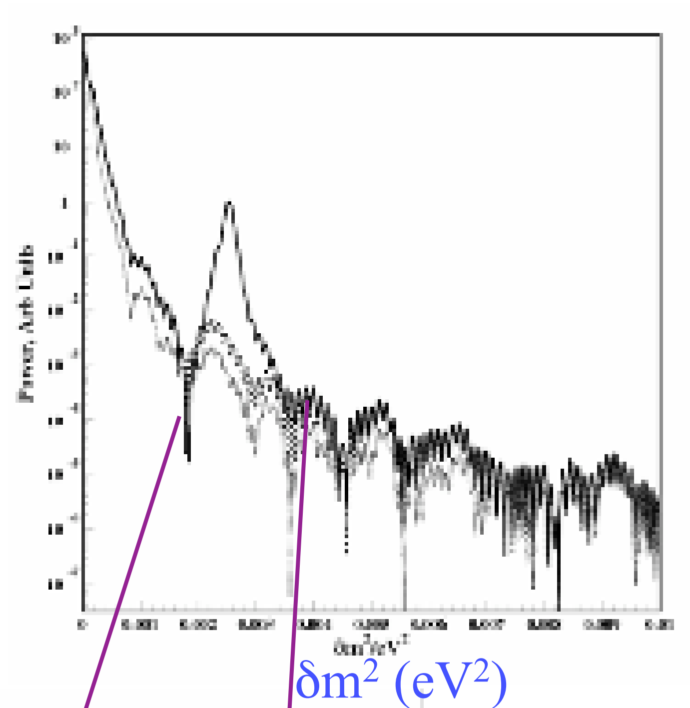
- Fourier transform data.
- At small δm2, we see the Δ_{21} modulation.
- The big peak is due to Δ_{31}.
- For **NORMAL** hierarchy, the Δ_{32} term will

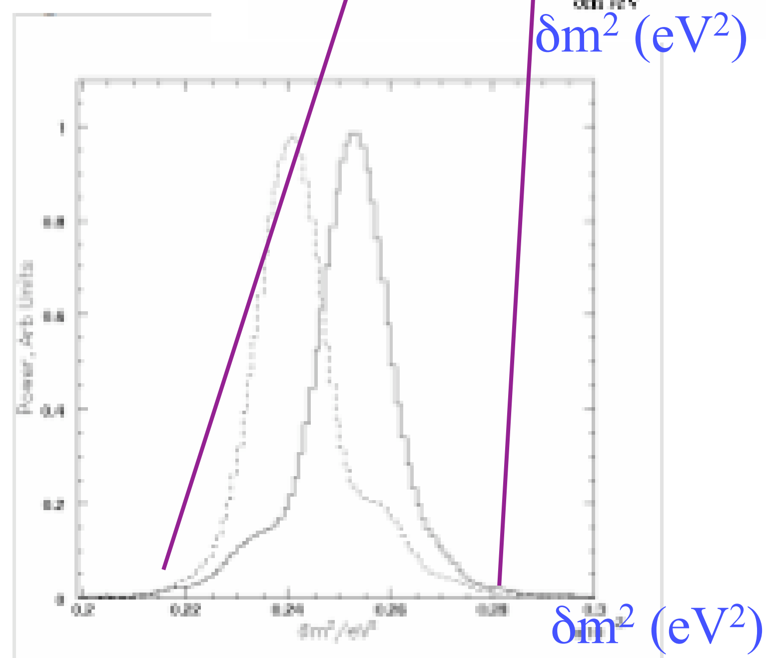
  have a slightly higher frequency,

  but a smaller amplitude.

  Bump on **RIGHT** side.
- For **INVERTED** hierarchy,

  Bump on **LEFT**side.





$P(\nu_e \text{--->} \nu_\mu)$

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

$$\pm \sin\delta_{CP}\ \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

$$+ \cos\delta_{CP} \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

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

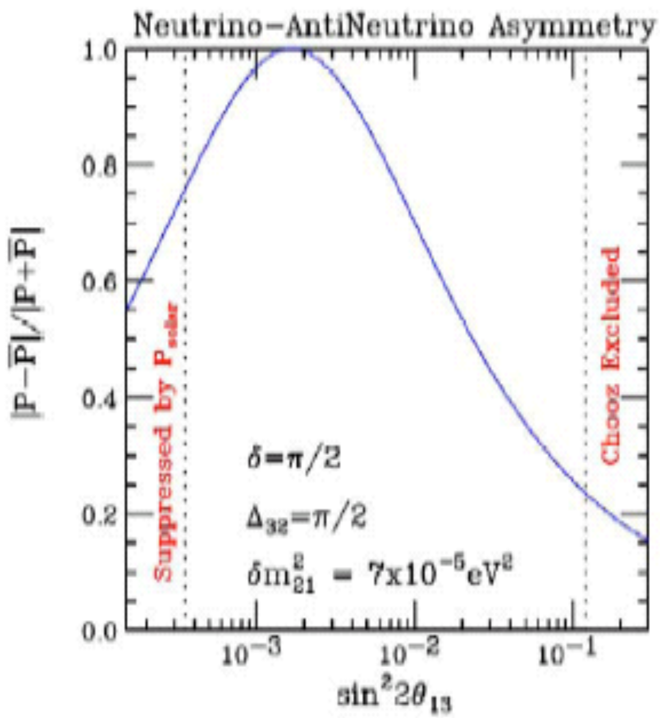
$$= F_1 \sin^2 2\theta_{13} + F_2\, \Delta_{21} \sin\delta \sin 2\theta_{13} + F_3\, \Delta_{21} \sin 2\theta_{13} + F_4\, \Delta_{21}{}^2$$

$$(P - \bar{P})/(P + \bar{P}) = \frac{2\, F_2\, \Delta_{21} \sin\delta \sin 2\theta_{13}}{2F_1 \sin^2 2\theta_{13} + 2F_3\, \Delta_{21} \sin 2\theta_{13} + 2F_4\, \Delta_{21}{}^2}$$

Behaviour of the CP asymmetry

$$(P - \bar{P})/(P + \bar{P}) = \frac{2 F_2 \Delta_{21} \sin\delta \sin 2\theta_{13}}{2F_1 \sin^2 2\theta_{13} + 2F_3 \Delta_{21} \sin 2\theta_{13} + 2F_4 \Delta_{21}^2}$$

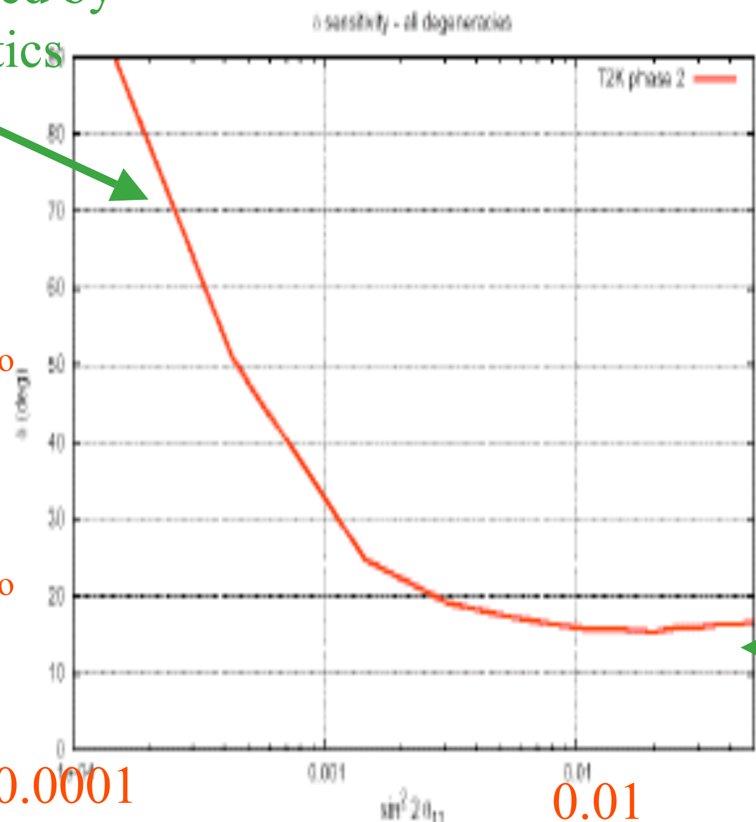
- Dropping the Δ_{21} terms, we see that the CP asymmetry goes **UP** with smaller θ_{13}.
- (But the oscillation probabilities go **DOWN.**)
- At some small value of θ_{13}, the F4 term becomes important. We can then ignore the F2 and F3 terms in the denominator and the asymmetry goes **DOWN** with θ_{13}.



T2K II: Sensitivity to δ_{CP}

Definition: For each value of $\sin^2 2\theta_{13}$:
The minimum δ for which there is a difference
Of 3σ between CP and NO CP violation

Limited by statistics



δ

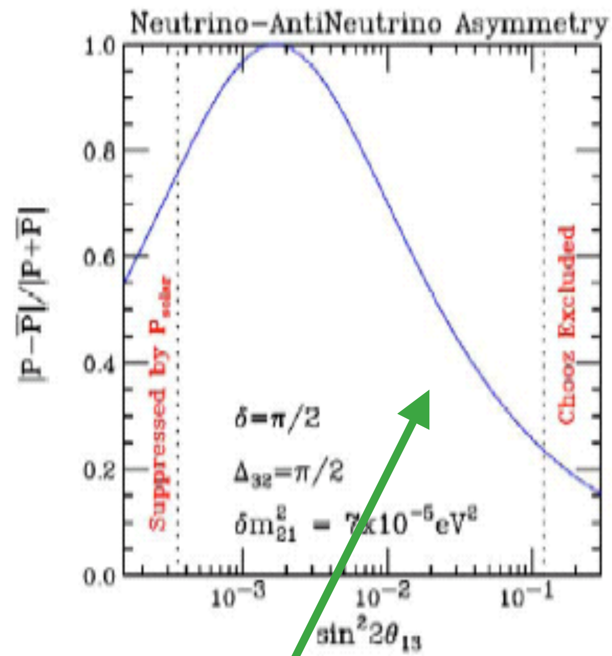
50°

20°

0.0001

0.01

$\text{Sin}^2 2\theta_{13}$



CP violation asymmetry ($\nu,\bar{\nu}$ difference) decreases with increasing $\sin^2 2\theta_{13}$

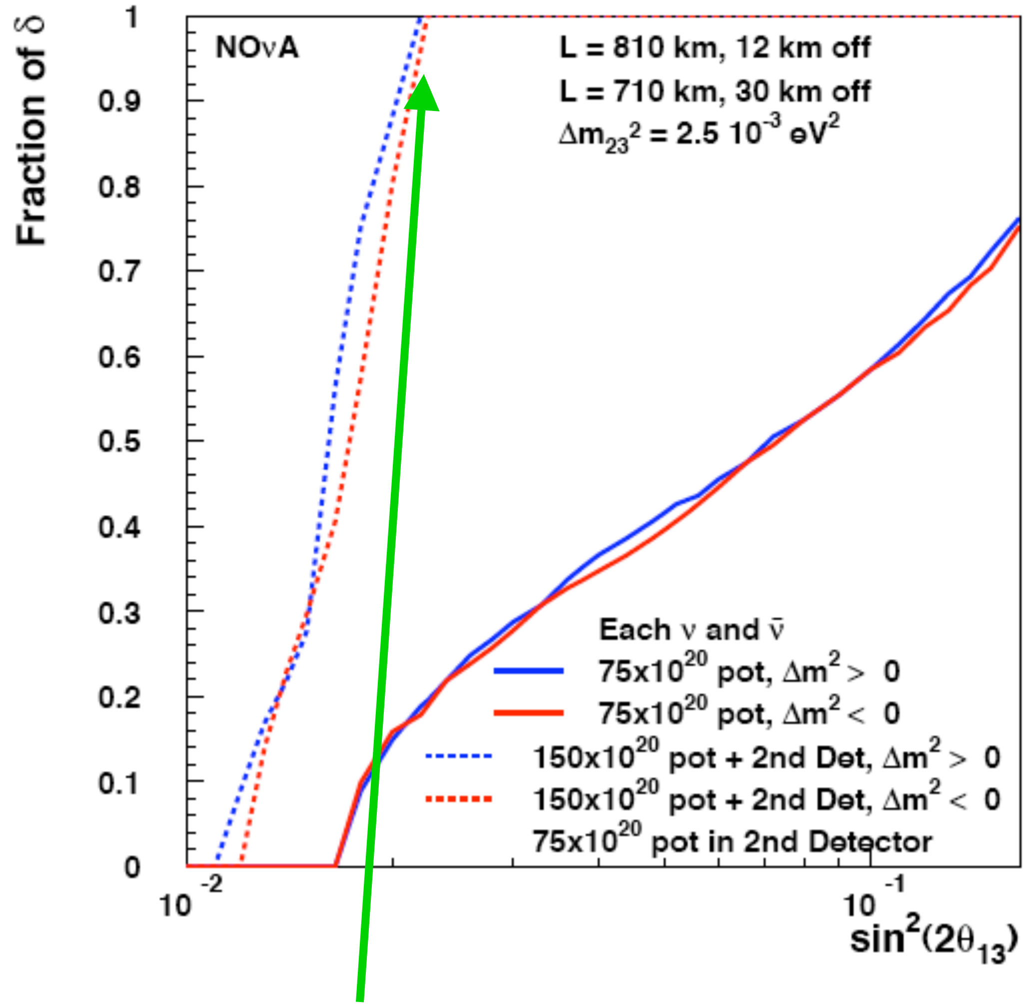
Looking further ahead

- With a proton driver, Phase II, the mass hierarchy can be resolved over 75% of δ near the CHOOZ limit.

- In addition to more protons in Phase II, to resolve hierarchy a second detector at the second oscillation maximum can be considered:

- $\Delta_{atm} = 1.27\ \Delta m^2_{32}\ (L/E) = 3\pi/2$. L/E = 1485, a factor of 3 larger than at 1st max.
  For ~ the same distance, E is 3 times smaller:
  matter effects are smaller by a factor of 3

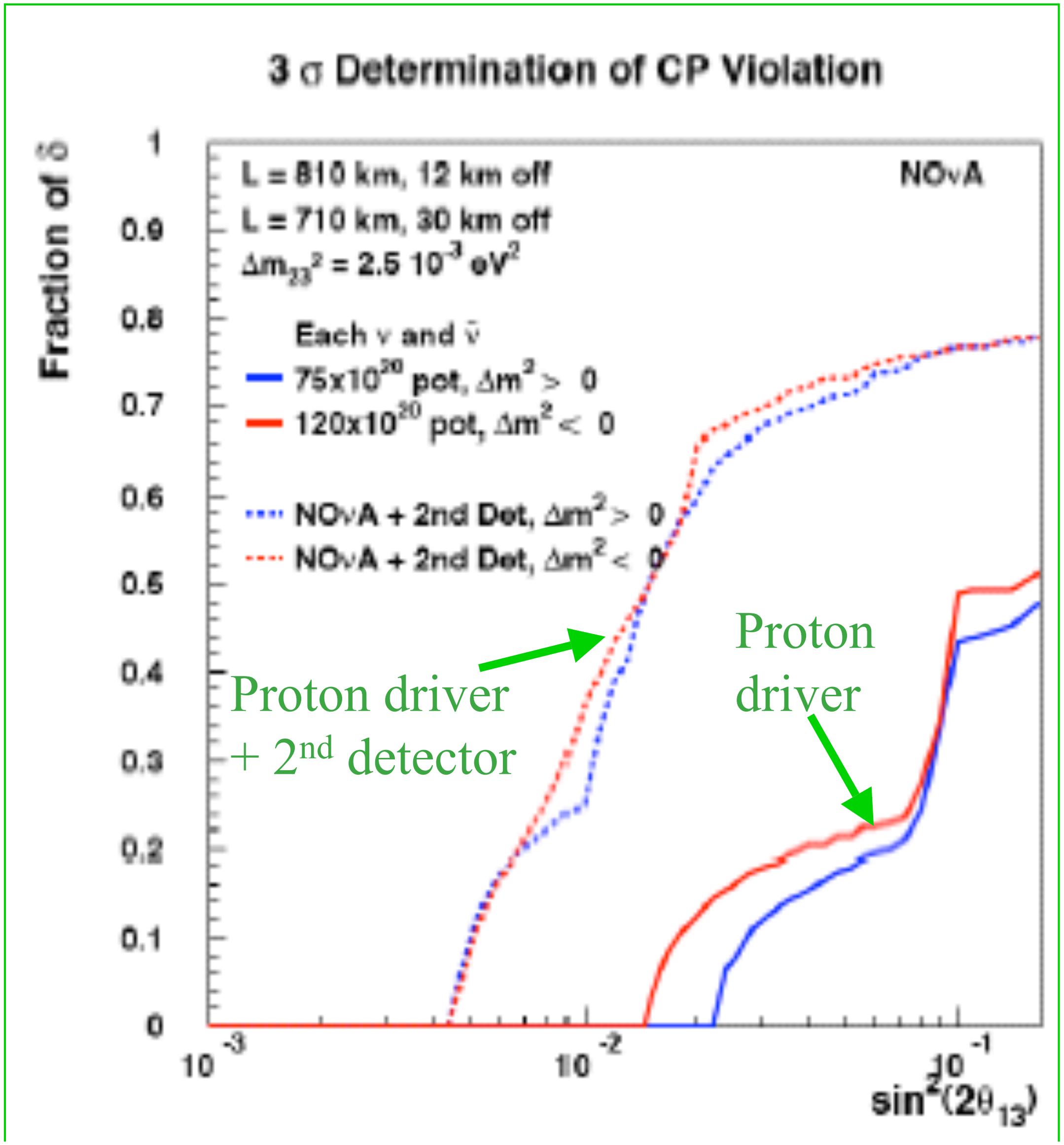
- 50 kton detector at 710 km.
- 30km off axis (second max.)
- 6 years $(3\ \nu + 3\ \overline{\nu})$



Determines mass hierarchy for all values of δ down to $\sin^2 2\theta_{13} = 0.02$

CP reach

- To look for CP violation requires the proton driver.
- But combining with a second detector is what really becomes SIGNIFICANT.



$$P(\bar{\nu}_e \rightarrow x) \approx \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

n,