Neutrino Oscillations

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Plan of the course

- A very brief theory of neutrinos and neutrino oscillations.

- The Past: The discovery of oscillations in
  - Solar and Atmospheric neutrino experiments.
  - Confirmation with man-made neutrinos.

- The Present programmes:
  - Direct neutrino mass measurements
  - Double-β decay
  - Reactors
  - Accelerator long baseline experiments.

- The Future:
  - Solar neutrinos at lower energy
  - Super beams
  - Radioactive ions beams
  - Neutrino factories

References

- The Neutrino Oscillation Web Page

  It has references to most

  - experiments,
  - theoretical papers,
  - conferences on neutrinos

  http://neutrinooscillation.org/

- Lepton-Photon Conference 2007 In Korea

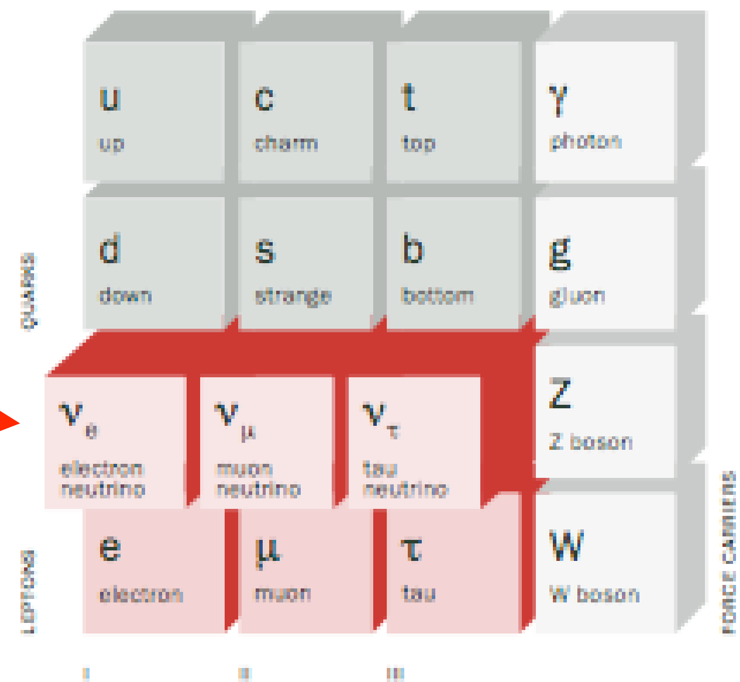
  http://chep.knu.ac.kr/lp07/htm/s11_01_01.htm

- Neutrino 2006 in Santa Fe (New Mexico)

http://neutrinosantafe06.com/page.php?pagename=sched

The family tree

Our subjects:
3 neutrinos

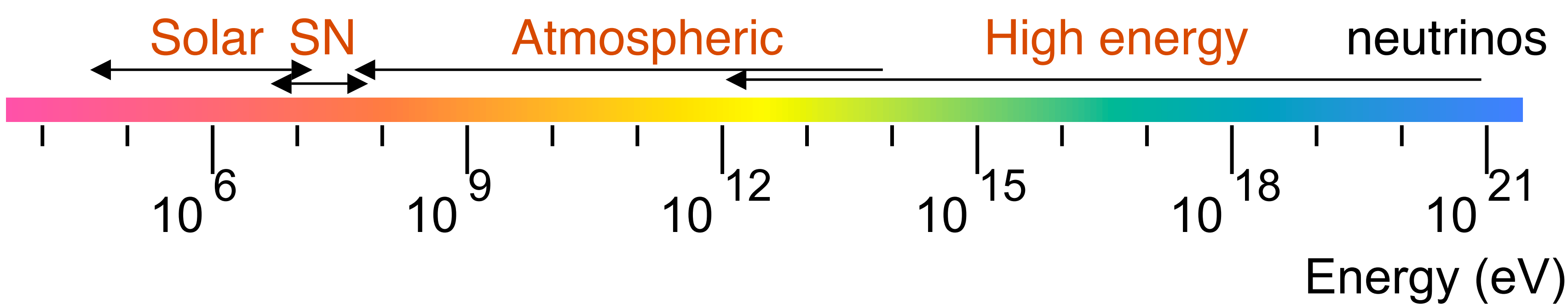


Diversity

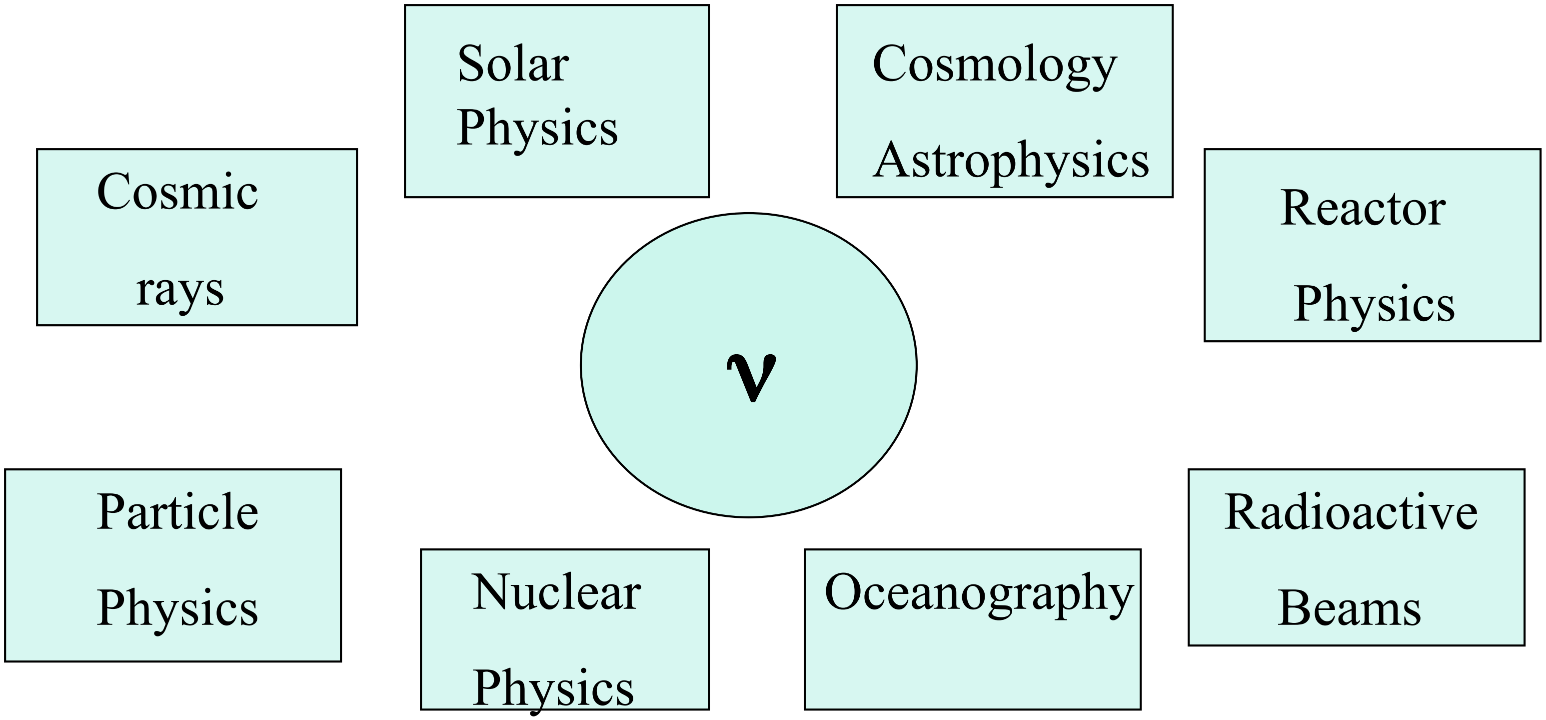
Sources of Naturally occurring Neutrinos (or Antineutrinos):

- Through decays of pions and kaons produced by cosmic rays: Atmospheric.
- Solar neutrinos
- Cosmogenic neutrinos from outer space.
- Geoneutrinos: from the earth interior: Radioactive decay.
- **Sources of man-made neutrinos:**
- Reactor neutrinos
- Accelerator-produced neutrinos.

Range in energy from 100 keV to 100's GeV.



Une page de pub:
Neutrino physics is fascinating!



- It also requires very diverse detection techniques because of the huge energy range they span
- And many different man-made production mechanisms such as reactors and accelerators.

The birth of the neutrino: a crisis!

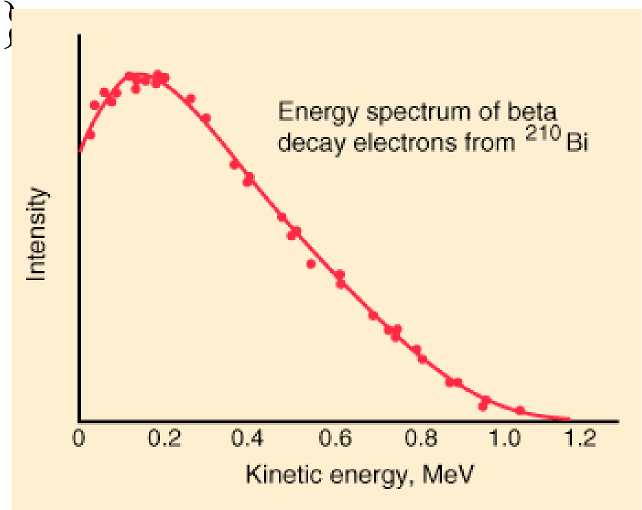
- Around 1910-1920 β decay was thought to be a 2-body process

$$A(Z) \to A(Z+1) + e^-$$

- By conservation of energy and momemtum the **electron** energy should be given by

$$E_e = \{ M^2(A,Z) - M^2(A,Z+1) + m_e^2\} / \{2M(A,Z)\}$$

- And therefore should be **MONOCHROMATIC.**
- In fact it was found to be a **CONTINUOUS** spectrum.
- Is momentum/energy conservation WRONG?



Solution suggested by Pauli:

there is a **third, neutral, particle** in the final state.

Pauli's Letter

WOLFGANG PAULI

Later changed to neutrino

After our present day neutron was discovered

Public letter to the group of the Radioactives at the district society meeting in Tübingen:

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dec. 1930
Gloriastr.

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and ^{6}Li nuclei and the continuous β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem"[3] of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin $\frac{1}{2}$ and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. – The continuous β-spectrum would then become understandable by the assumption that in β-decay, a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and electron is constant.

– So, dear Radioactives, examine and judge it. – Unfortunately I cannot appear in Tübingen personally, since I am indispensable here in Zürich because of a ball on the night of 6/7 December. – With my best regards to you, and also to Mr. Back, your humble servant, !

W. Pauli

Fermi

- 1934:

Fermi postulated a point-like interaction
Between 4 particles:

- Proton
- Neutron (discovered by Chadwick)
- Electron
- Neutrino

With a **WEAK** coupling strength.

This eventually was unified with electromagnetism
And is now the Standard Model of Electroweak Interactions.

The first (anti)neutrino events

- Difficulty in detecting a neutrino: It's interaction cross-section!

- For the reaction: $\bar{\nu} + p \rightarrow n + e^+$ at an antineutrino energy of 2 MeV
  (This is inverse beta decay $n \rightarrow p + e^- + \bar{\nu}$)

  $\sigma = 10^{-44}$ cm^{-2}. It can travel **1600 light** years in water without interaction.

- Solution: Very intense neutrino source and very massive detectors.

- In 1953 this became feasible with the advent of nuclear reactors.

  $$n + {}_{92}U^{235} \rightarrow (A_1, Z[\sim 46]) + (A_2, 92\text{-}Z) + \text{neutrons}$$

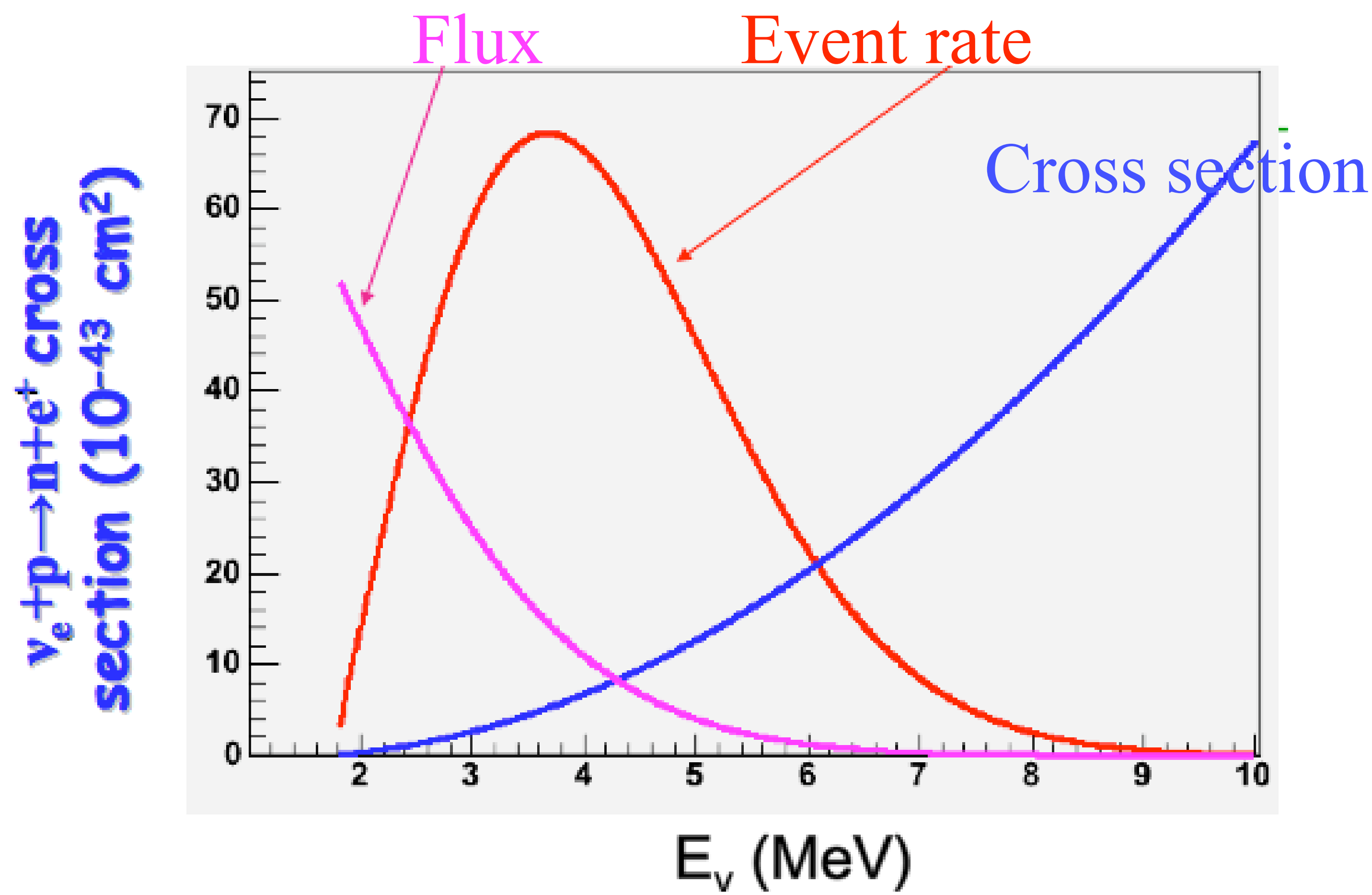
- A_1 and A_2 then decay in a cascade emitting **(anti)NEUTRINOS** ending with stable nuclei.

- $(A_{1,2},Z) \rightarrow (A_{1,2},Z+1) + e^- \bar{\nu}_e$ $(A_{1,2},Z+1) \rightarrow (_{A1,2}, Z+2) + e^- \bar{\nu}_e$ …….

- On average: **6** antineutrinos per nuclear fission

- **5.6×10^{20} antineutrinos/sec** for a reactor power of $3GW_{th}$.

Reactor event rate



Event rate peaks at 3 - 4 MeV

The first (anti)neutrino events

- Detected by Reines and Cowan using a reactor at Savannah River
- Using the reaction $\bar{\nu}$ + p -> n + e^+
- In a target consisting of water and cadmium.

Prompt signal

$$e^+ + e^- \rightarrow 2\gamma$$

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

Capture on Cd, emits photons

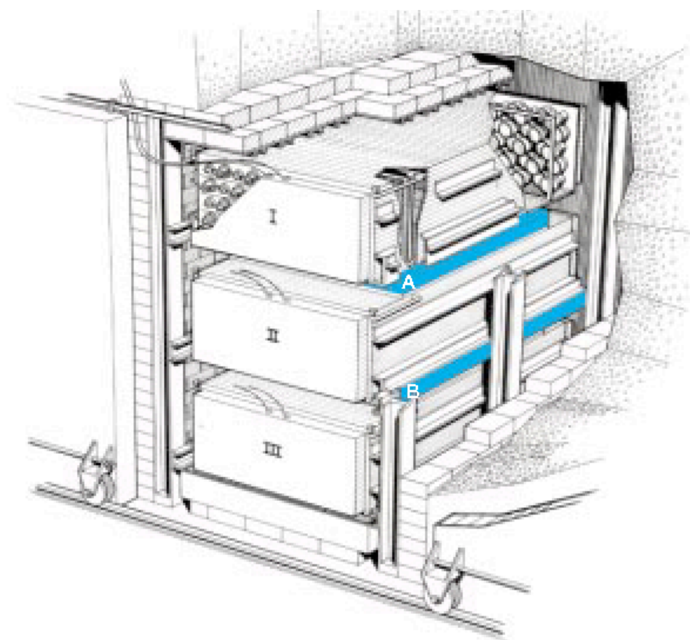
Delayed signal

Allows a coincidence

Reduction of background

- They found a rate of

Reactor ON - Reactor OFF = 3.0 ± 0.2 events/h

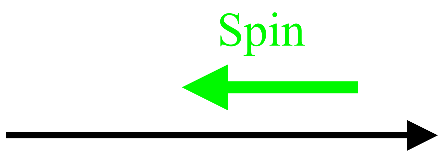


Properties

- Neutrinos are massless.

- They have spin 1/2

- Neutrinos are left-handed
  Spin **anti-parallel** to motion



- Antineutrinos are right-handed
  Spin **parallel** to motion

- Since they are massless, they will keep their
  Handedness whatever frame of reference they are in.

Another one

- The π meson was discovered and found to decay: $\pi^- \to \mu^- + \nu$
- The μ was found to decay to an electron. But because the electron energy was not monochromatic, it was thought to be a

  3-body decay $\mu \to e + \nu + \nu$
- Why didn't $\mu \to e + \gamma$ happen? Energetically possible.
- Introduce Muon number, Electron number + Conservation.
- Negative muon has muon number **+1**, Electron number **0**
- Electron has electron number **+1**, muon number **0**.
- But then the neutrinos produced in π and μ decay have to be special:
- $\pi^- \to \mu^- + \bar{\nu}_\mu$ and $\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$

	π^-	μ^-	$\bar{\nu}_\mu$	μ^-	e^-	ν_μ	$\bar{\nu}_e$
Muon #	0	+1	-1	+1	0	+1	0
Elec. #	0	0	0	0	+1	0	-1

- IMPLICATION: ν_μ and ν_e are different.

Another two…

- Are they really different?
- **YES.** At Brookhaven used a beam of neutrinos from π decay.
- They interacted giving μ^- in the final state but NOT e^-. ν_μ.

- Proof that there were two different neutrinos.

- Neutrinos are also produced together with tau leptons (τ).

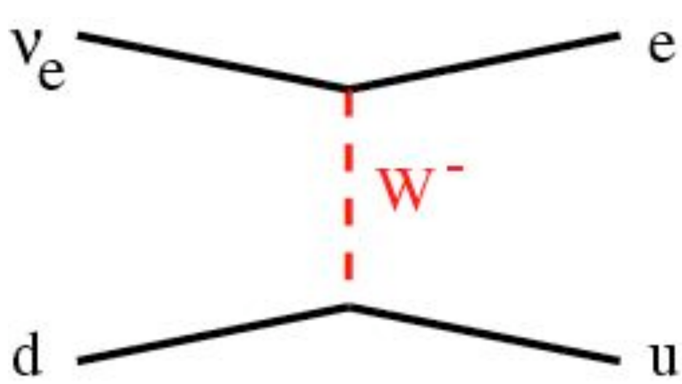
  Also different. ν_τ

Interactions

Neutrinos can either interact via:

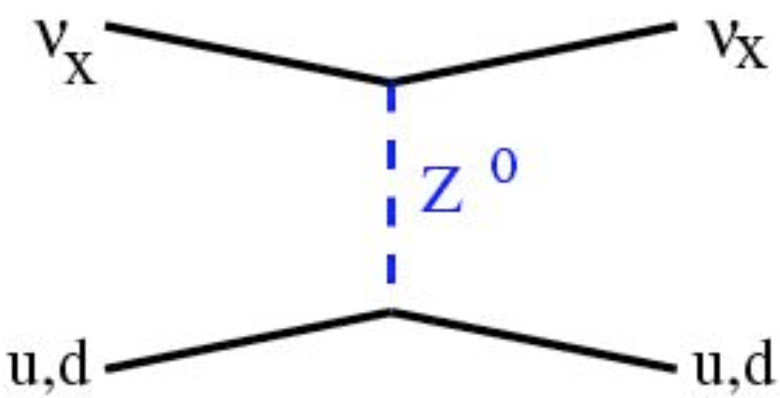
Charged currents.

Exchange of a W.



Or neutral currents.

Exchange of a Z^0.



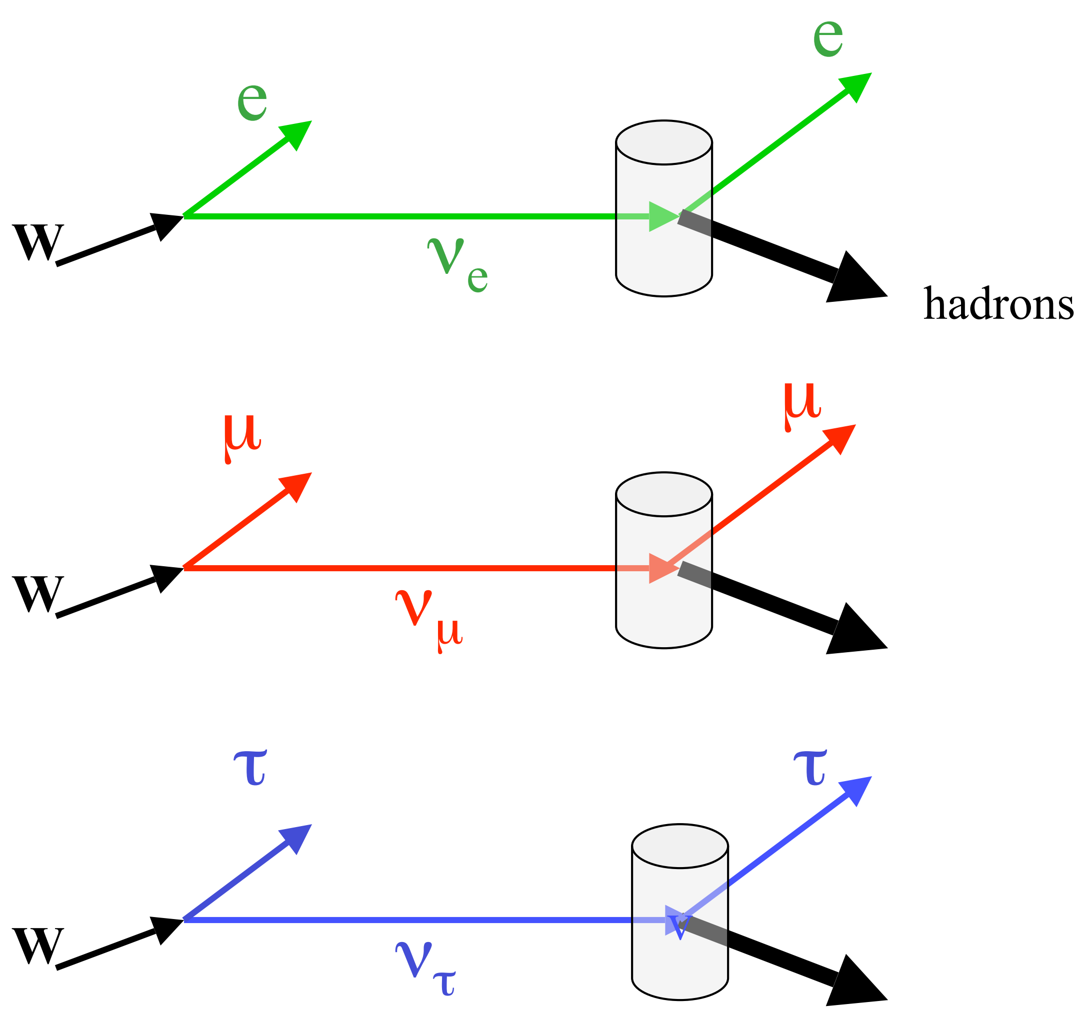
How do they interact ?

A neutrino produced
together with:

a) An **electron**
Always gives an **electron**
Through a charged current

b) A **muon**
Always gives a **muon**
Through a charged curent

c) A **tau**
Always gives a **tau**
Through a charged current



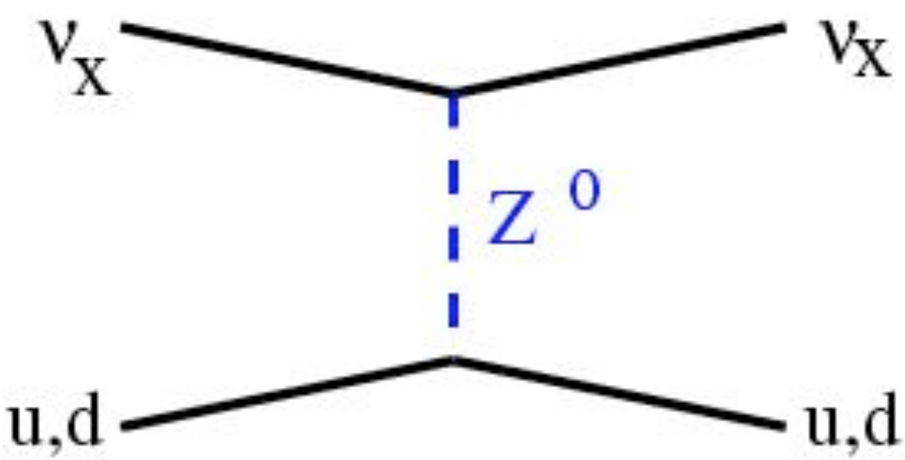
They are different !

I lie. Not ALWAYS !!!

- Only true for short distances between production and interaction (observation).

- The subject of this course is to convince you that for long distances things are different.

Neutral Currents



In a neutral current interaction
The flavour of the **final** state neutrino
Is always the **same** as the flavour of the **initial** state neutrino

ν_e remains ν_e, ν_μ remains ν_μ, ν_τ remains ν_τ

No flavour changing neutral currents

Two puzzles:
I. The missing solar neutrinos

- Nuclear reactions in the sun produce a large of flux of neutrinos, ν_e's .
- They have been observed in several experiments.
- The flux can be calculated.
- The observation gave results significantly **smaller** than predictions.
- **Why?**
  - Are the calculations wrong?
  - Are the neutrinos disappearing en route?
  - The detectors were only sensitive to ν_e's.

    Are they changing from one neutrino type to another?

II. The missing atmospheric neutrinos.

- Cosmic rays interacting in the upper atmosphere produce π and K mesons.
- They decay to ---> $\mu + \nu_\mu$.
- Then the muons decay to $e + \nu_e + \nu_\mu$
- So the ratio of ν_μ / ν_e should be 2.

- Found to be 1.

- **Why?**
  - Wrong particle production?
  - Some neutrinos disappearing en route?
  - One type changing to another?

Theory of Oscillations

$$\sum_{k=1,3} U^*_{ik} U_{jk} = 0 \text{ for } i \neq j$$

Assumptions:

- Neutrinos have masses.
- Neutrinos mix. Their mixing is described by a Unitary matrix U, similar to the
  Cabibbo Kobayashi Maskawa (CKM) mixing matrix for quarks.

- The 3 **weak (flavour)** eigen states $|\nu_f>$, with f = e ,μ, τ
  are linear superposition of 3 **mass states** $|\nu_k>$, with k = 1, 2 , 3, such that

$$|\nu_f> = \sum_{k=1}^{3} U_{fk} |\nu_k>$$

With U =

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

Flavour state expansions

$$\nu_e = U_{e1}\,\nu_1 + U_{e2}\,\nu_2 + U_{e3}\,\nu_3$$

$$\nu_\mu = U_{\mu 1}\,\nu_1 + U_{\mu 2}\,\nu_2 + U_{\mu 3}\,\nu_3$$

$$\nu_\tau = U_{\tau 1}\,\nu_1 + U_{\tau 2}\,\nu_2 + U_{\tau 3}\,\nu_3$$

$$|\,\nu_f > \; = \sum_{k=1} U_{fk}\,|\,\nu_k >$$

With U =
$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

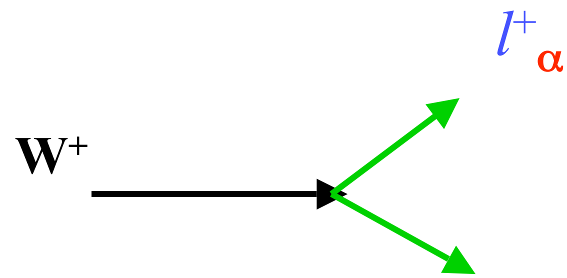
Antineutrinos

$$|\bar{\nu}_f> = \sum_{k=1}^{3} U^*_{fk} |\bar{\nu}_f>$$

W decay revisited

$W^+ \text{--->} l^+_\alpha + \nu_\alpha$

$\alpha = e, \mu, \tau$



$\nu_\alpha = \sum_k U_{\alpha k} |\nu_k>$

Given flavour α Given mass state k

When a neutrino of flavour α , $\nu_{\alpha,}$ is produced together with a charged lepton α,
It contains all 3 mass states ν_k's .

Each ν_k with an amplitude given by $U_{\alpha k}$ or a probability $| U_{\alpha k}|^2$

Mass states expansions

- Similarly each mass state is a superposition of flavour states:

$$\nu_k = \sum_\alpha \; U^*_{\alpha k} \, |\nu_\alpha>$$

$$\nu_1 = U_{e1}\,\nu_e + U_{\mu 1}\,\nu_\mu + U_{\tau 1}\,\nu_\tau$$

$$\nu_2 = U_{e2}\,\nu_e + U_{\mu 2}\,\nu_\mu + U_{\tau 2}\,\nu_\tau$$

$$\nu_3 = U_{e3}\,\nu_e + U_{\mu 3}\,\nu_\mu + U_{\tau 3}\,\nu_\tau$$

And the fraction of flavour α in mass state ν_k is given by

$$<\nu_\alpha \,|\, \nu_k> = |U_{\alpha k}|^2$$

Theory 3

At time t = 0 we produce a beam of a given flavour ν_α

Then at time t = t

E_i and m_i should be E_k an m_k

$$|\nu_\alpha(t)> = e^{ip.r} \sum_{k=1}^{3} U_{\alpha k}\ e^{-iE_i\,t}\ |\nu_k>$$

$$= e^{ip.r} \sum_{k=1}^{3} U_{\alpha k}\ e^{-i\sqrt{(p^2+m_i{}^2)}t}\ |\nu_k>$$

The different $|\nu_k>$ will evolve differently with time

because of the different m_k's in the exponent

- CONSEQUENCE:

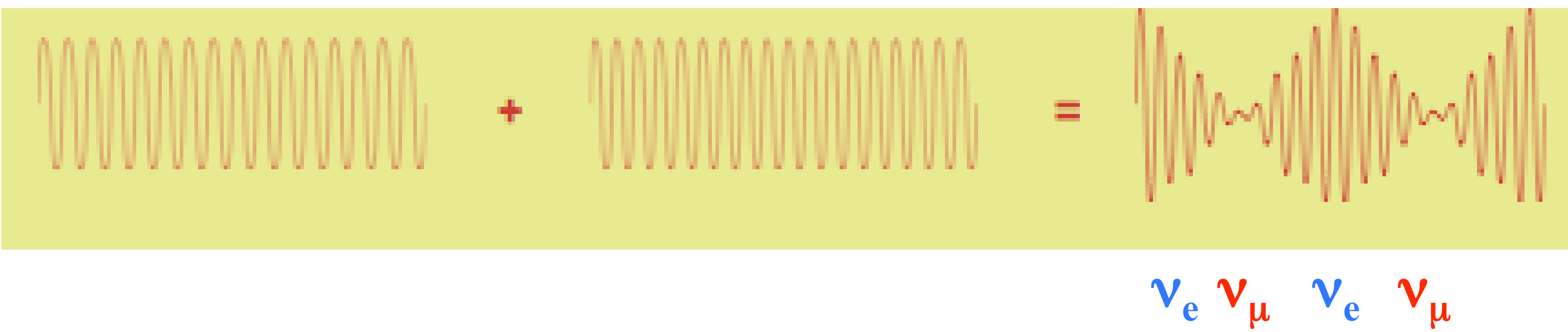
➢ At t = 0, we had the exact mix of mass states to represent the flavour state ν_α

➢ At t = t, we now have a **different** mix of mass states and therefore

All flavours are present in the beam at some level.

Waves

When two waves with similar frequency add, they interfere and produce beats.



Theory 5

FOR OSCILLATIONS TO OCCUR:

- NEUTRINO MUST HAVE **NON-ZERO** MASSES .

- AND THE 3 MASS STATES MUST HAVE **DIFFERENT** MASSES

Theory 4

U is usually represented as a product of three rotations

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

δ is a phase.

Neutrinos

Antineutrinos

If $\delta \neq 0$ then **U** $\neq$ **U***

Induces **DIFFERENT** behaviour for neutrinos and antineutrinos

$\nu_e \dashrightarrow \nu_\mu$ oscillation $\neq$ $\bar{\nu}_e \dashrightarrow \bar{\nu}_\mu$ oscillations

----> **CP violation**

Theory 6: Two-neutrino mixing.

- We limit ourselves (TEMPORARILY) to **2** neutrinos.

- The mixing can be described by a simple rotation

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$\theta \Rightarrow$ STRENGTH of oscillation.

Starting with a beam of flavour α at time t=t

$$|\nu(t)> = e^{ip.r} \left(\cos\theta e^{-iE_1 t} |\nu_1> + \sin\theta e^{-iE_2 t} |\nu_2>\right)$$

Theory 7

Probability to find the flavour β in the initially pure α beam:

$$P_{\alpha\beta} = | < \nu_\beta(t) \mid \nu_\alpha > |^2$$

With $| \nu_\beta > = -\sin\theta \, | \nu_1 > + \cos\theta \, | \nu_2 >$

$$P_{\alpha\beta}(t) = \sin^2 2\theta \sin^2 \frac{(E_1 - E_2)}{2} t$$

With

$$E_{1,2} = \sqrt{p^2 + m_{1,2}^2} \simeq p\left(1 + \frac{m_{1,2}^2}{2p^2}\right)$$

Setting

$$\Delta m^2 = (m_1^2 - m_2^2) \quad \text{and} \quad t = L/c$$

(L = distance between production and observation)

Theory 8

Probability to find the flavour β in the initially pure α beam:

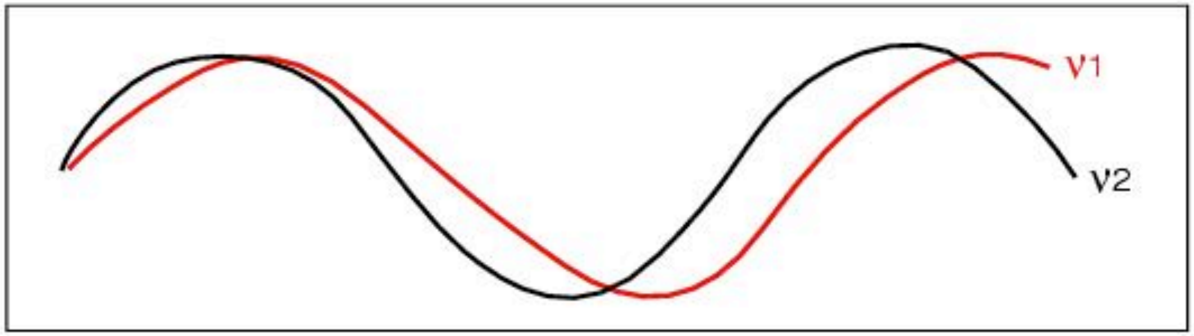
$$P_{\alpha\beta}(t) = \sin^2 2\theta \sin^2 1.27 \frac{L(m)}{E(MeV)} \Delta m^2 (eV^2)$$

$$\Delta m^2 = m_1^{\ 2} - m_2^{\ 2}$$

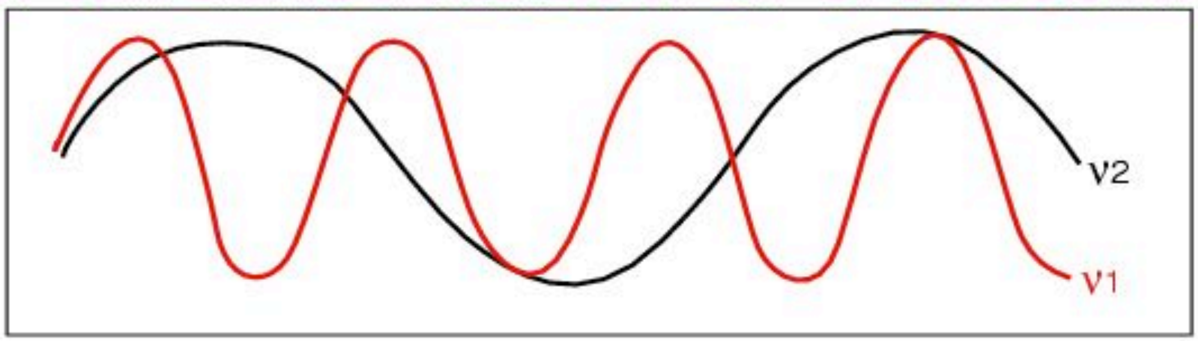
Probability for the flavour α to “survive” unchanged:

$$P_{\alpha\alpha}(t) = 1 - P_{\alpha\beta}(t)$$

$$P_{\alpha\beta}(t) \;=\; \sin^2 2\theta \, \sin^2 1.27 \frac{L(m)}{E(MeV)} \Delta m^2 (eV^2)$$



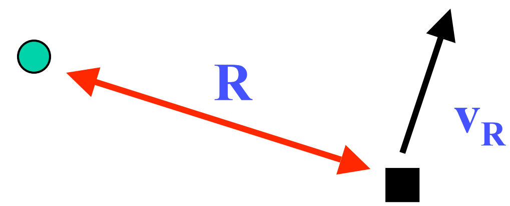
SMALL differences between m_{ν_1}, m_{ν_2}: mix of mass states will NOT change quickly.
ν's must travel FAR to have an appreciable probability to oscillate to another flavour.
MUST COMPENSATE SMALLNESS OF Δm^2 BY LONG DISTANCES.



LARGE mass differences: the mix changes very quickly $\longrightarrow$ Fast oscillations.
Many oscillations within Detector or Source size. Averages: P= $\frac{1}{2}$ $\sin^2 2\theta$.

Can we solve another puzzle with ν's ?

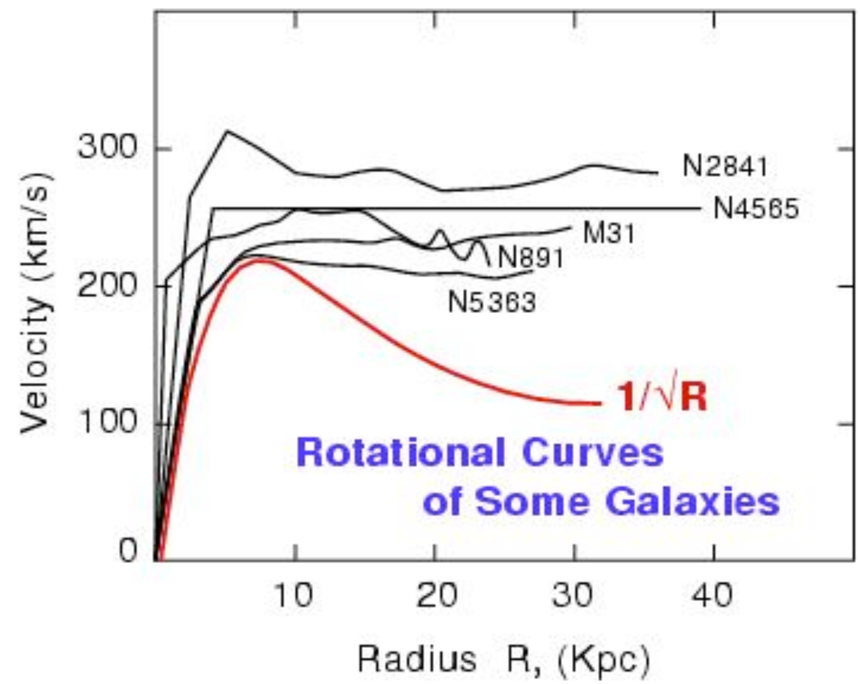
- We have seen that ν's need to have mass for oscillations to occur.
- If they DO have mass can we use them to explain the DARK MATTER puzzle?



The DARK MATTER PUZZLE

- Observation of the rotational velocity of matter in galaxies:
- Should decrease as $1/\sqrt{R}$ because less and less matter enclosed in the orbit.
- Instead: observed to remain flat at large distances. Zwicky ~ 1937.
- Possible explanation: we enclose more matter than we think as we go out in distances, but

  this matter is invisible to us: DARK.
- Or is the law of gravitation modified?



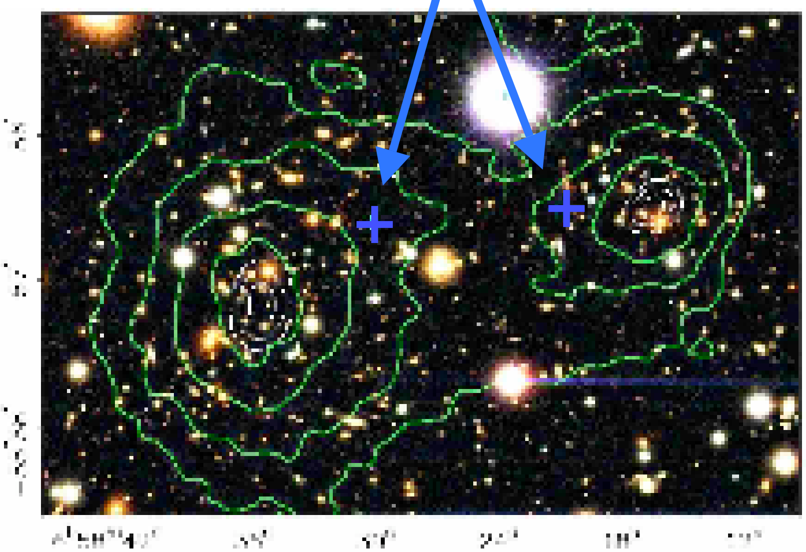
Recent evidence for Dark Matter

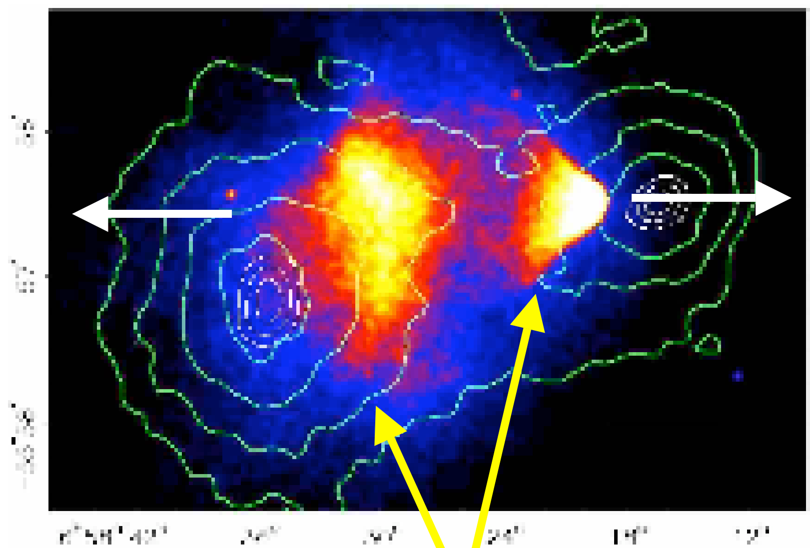
Normally, stars (5%), plasma (15%) and Dark matter coincide in a galaxy cluster

During a collision of 2 clusters, the plasma (a fluid) is retarded. Stars will not.

If no DM, (modified law) gravitational potential will coincide with plasma (most mass).
It does not.

Centres of plasma distributions





Gravitational potential distribution: Determined from gravitational lensing

There REALLY is

Something else

Plasma distribution:

Determined by X-ray emission .

Neutrinos as Dark Matter

- What could **DARK MATTER** be?
- One "object" that is very abundant and "unseen" in the universe:

  RELIC NEUTRINOS from the Big Bang

(equivalent to the Cosmic Microwave Background Radiation (CMBR) photons, $\mathbf{n_\gamma}$)

- DENSITY: $\rho = (3/11)\, \mathbf{n_\gamma} \sum^{3}_{i=1} \bar{m}_i$ with i = 1 - 3 the 3 neutrino mass states.

- $115/\text{cm}^3$ (neutrinos + antineutrinos) per neutrino species.

- Their cosmic mass fraction: $\Omega(\nu\nu)\, h^2 = \sum m_\nu/(92.5 \text{ eV})$
- h = Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$

- If they had an average mass of **$30 \text{ ev}/c^2$**, they could explain the observation.
- But are they of low enough energy to be trapped in gravitational fields such as clusters?

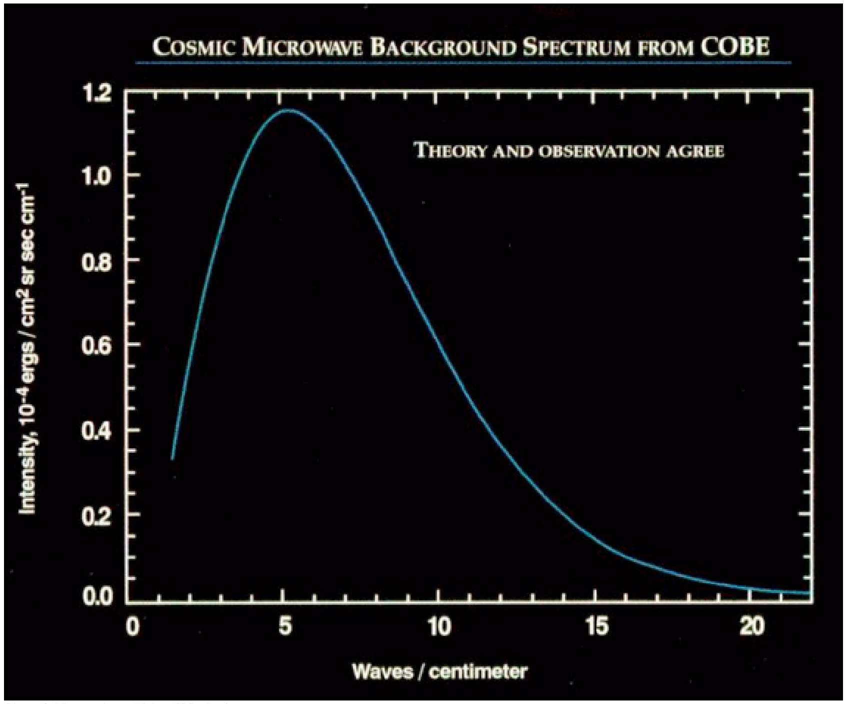
Black body spectrum

We know that the temperature of the cosmic microwave background radiation is **2.728°K.**

Measured by WMAP, COBE etc…

From the shape of the photon energy spectrum: Perfect black body.

Do neutrinos have the same temperature?



Neutrino temperature

- Originally photons are in equilibrium with electrons:
- Electrons or positrons radiate photons: **$e^{\pm}$ --> $e^{\pm}$ + γ**
- And photons pair produce: **γ --> e^{+} + e^{-}**

- As the universe cools, the energy of the radiated photons falls below **$2 \times m_e = 1$ MeV**, and they can no-longer pair produce.
- All the electron energies are therefore gradually **transferred** to the photons.
- This results in an increase of the photon temperature by **x 1.4.**

- Since this does not happen for neutrinos, we deduce that
- **$T_\nu = T_\gamma / 1.4 = 1.95^o$K or 2×10^{-4} eV**
- So a 30 eV neutrino would be non-relativistic and “trappable”.

The search: NOMAD, CHORUS.

- Assume the lightest neutrino mass state has a mass ~ zero
  Then the mass difference we should be investigating is
  $\Delta m^2 = (30\ eV - 0)^2 = 900\ eV^2$.

- Mental bias: Since the τ lepton is the heaviest charged lepton
  its partner, the ν_τ, should contain a high proportion of the highest mass state ~ 30 eV.

- Look for ν_μ ----> ν_τ oscillations at $\Delta m^2 \sim 900\ eV^2$.

- Two experiments: CHORUS and NOMAD,

- Designed to detect the **appearance of** ν_τ in a ν_μ beam.

- ν_τ detection via its charged current interaction: $\nu_\tau + X \dashrightarrow \tau + X'$. Search for τ's.

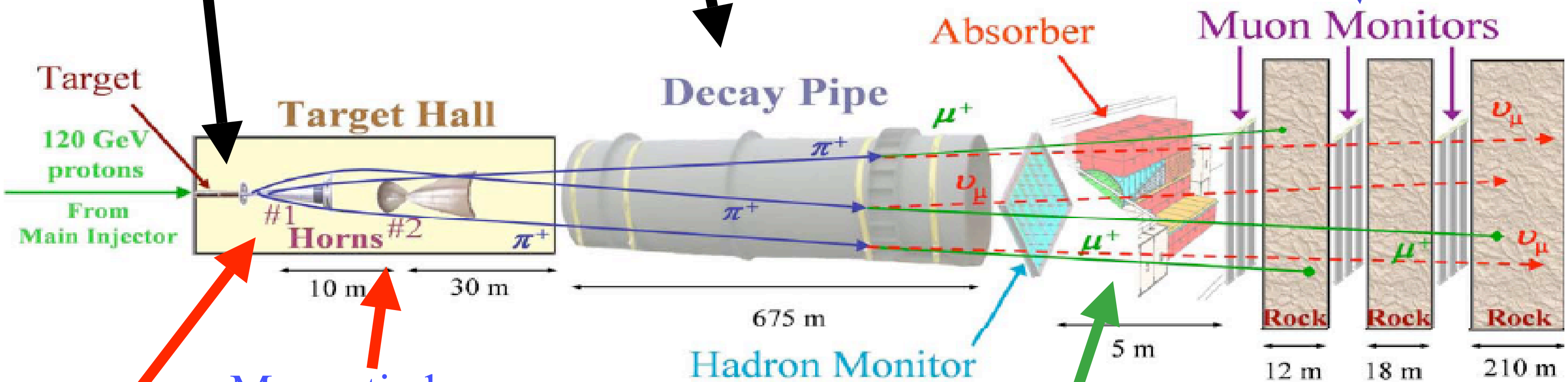
- **How do we produce a neutrino beam with an accelerator?**

A Neutrino beam.

Protons interact
In target producing
π,K

Decay pipe to give mesons
time to decay
$\pi, K \longrightarrow \mu + \nu_\mu$

Muon counters: allows
estimate of neutrino flux

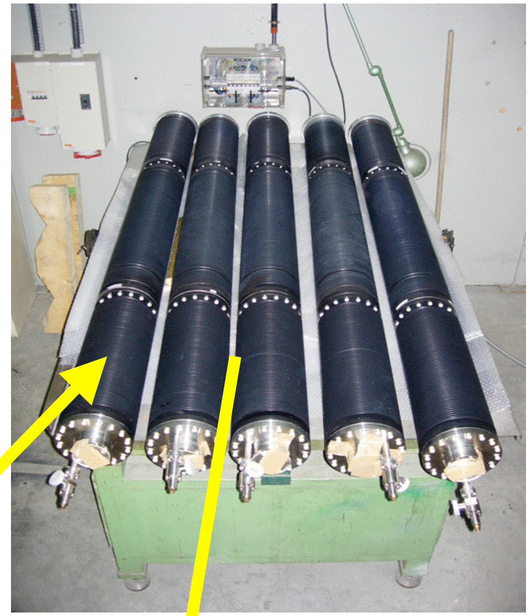


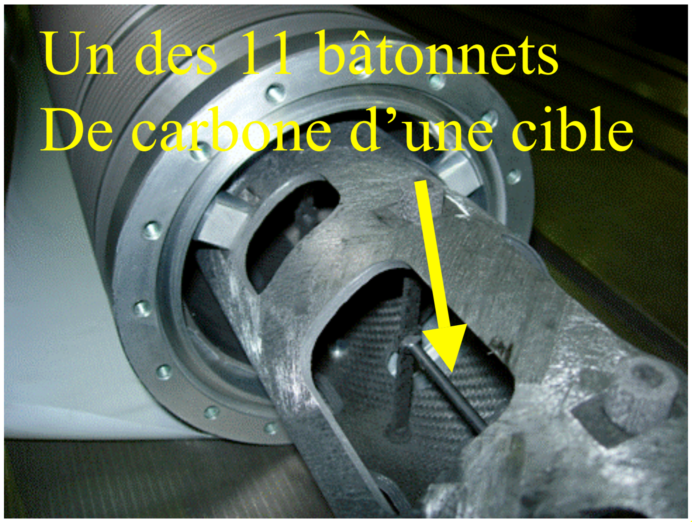
Magnetic horns
Focus +ve mesons
for neutrino beam
or
Reverse polarity and
Focus negative mesons
for antineutrino beam

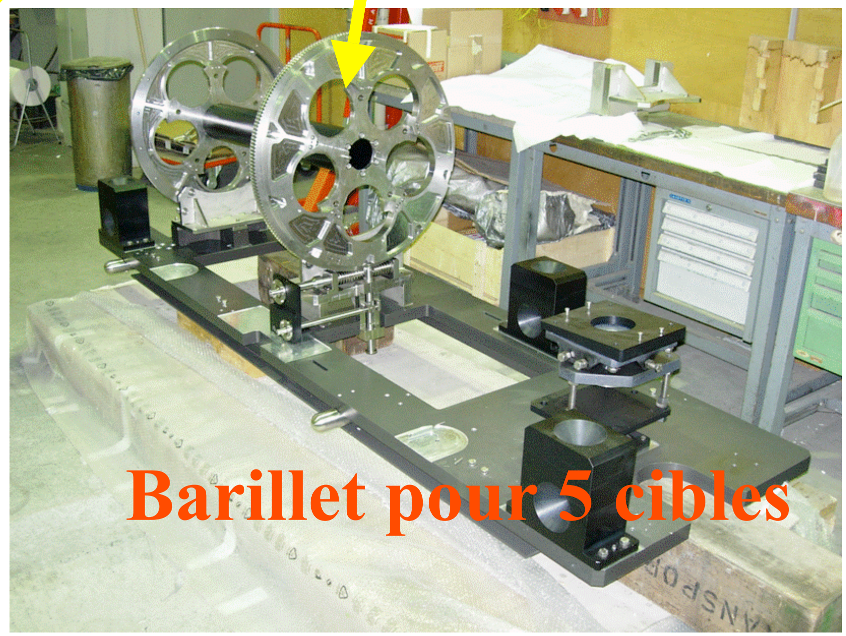
Absorber to get rid of
non-interacting protons
and remaining mesons

The target

The target must be
made of target rods
long (many p interactions)
thin (avoid π,K reinteractions)



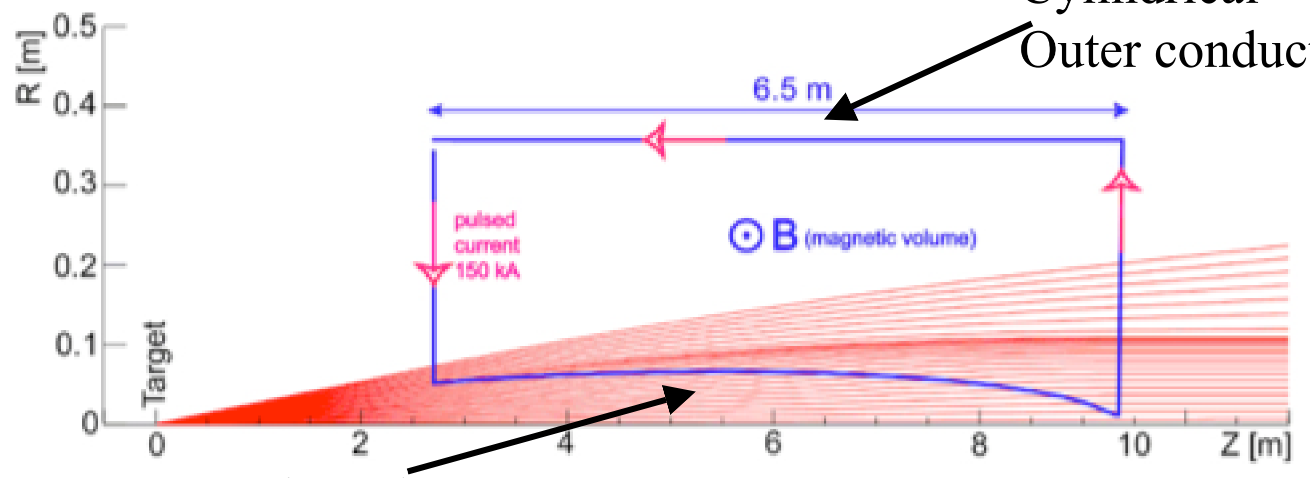




The magnetic horn principle

Transforms the diverging particles coming out of the target
into a near parallel beam

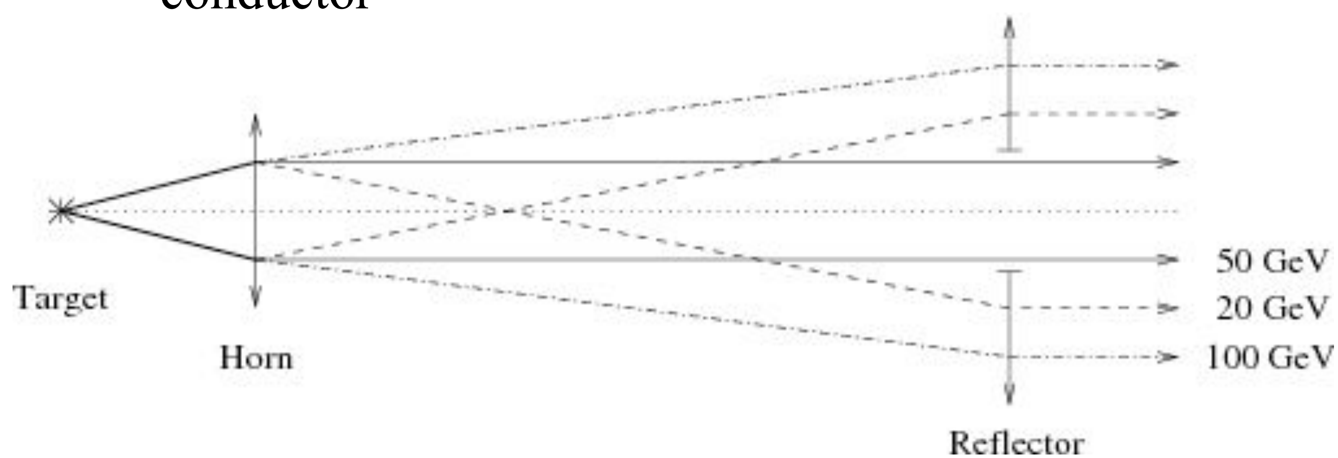
Cylindrical
Outer conductor



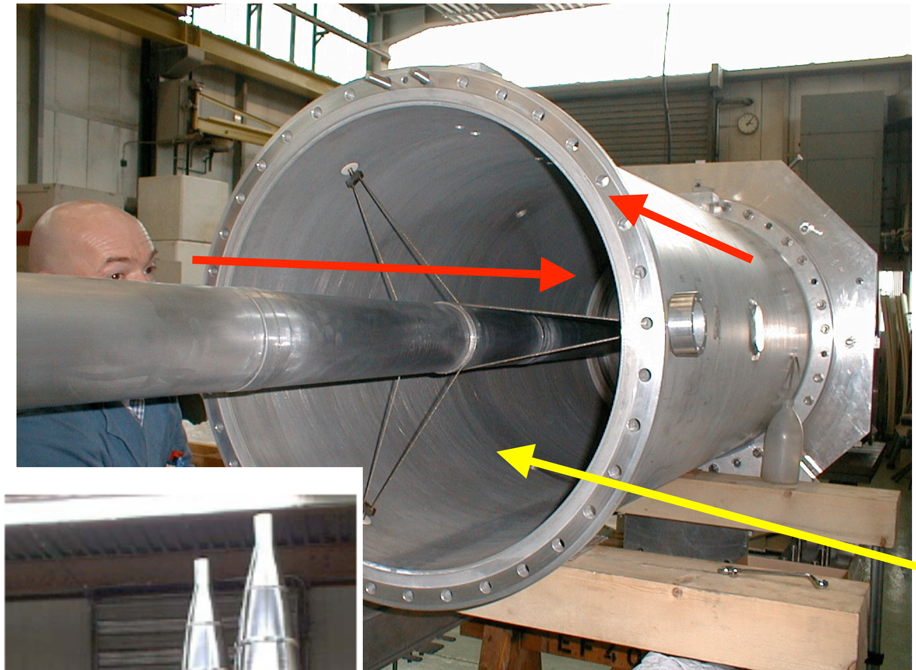
Shaped Inner
conductor

Optimized for a given
momentum range

Need a second one
To increase the range



La corne



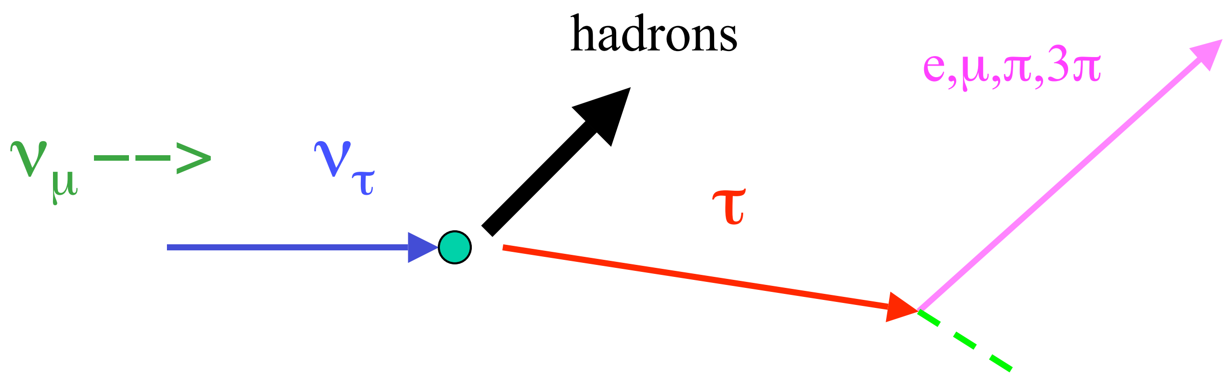
Current sheet on outer conductor
Return path on
Inner conductor

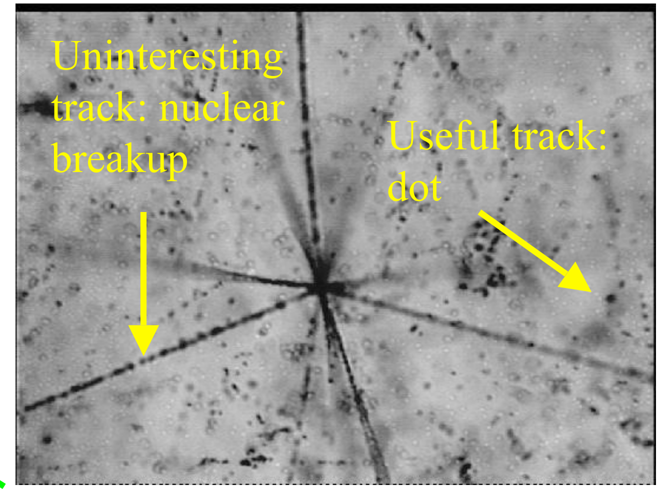
Produces a
toroidal magnetic field
between the two conductors
~ 1/R

Inner conductor

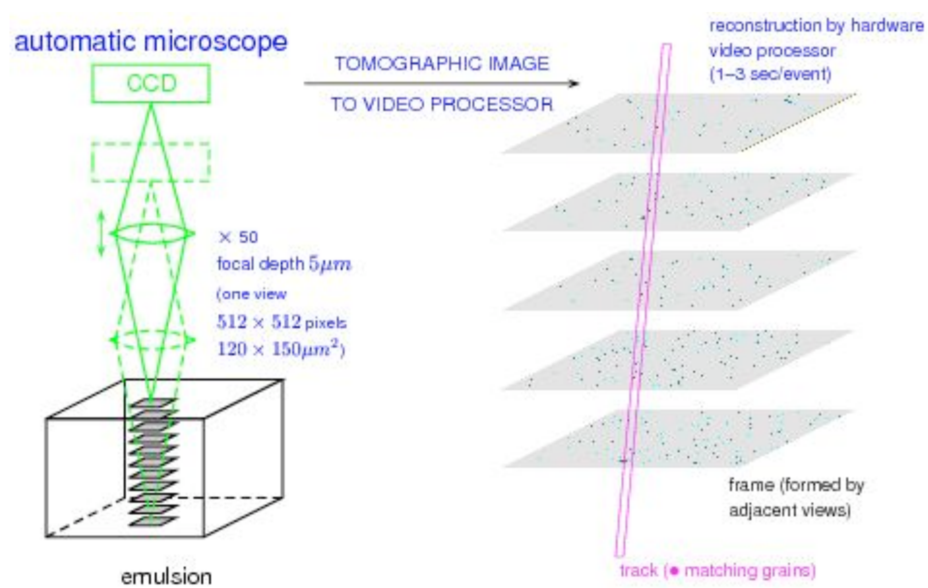
Need a current of **>100kA** Cannot sustain it DC
Charge condensers and
Discharge in time with passage of beam ~ **a few μsecs.**

Two methods to detect a τ : CHORUS

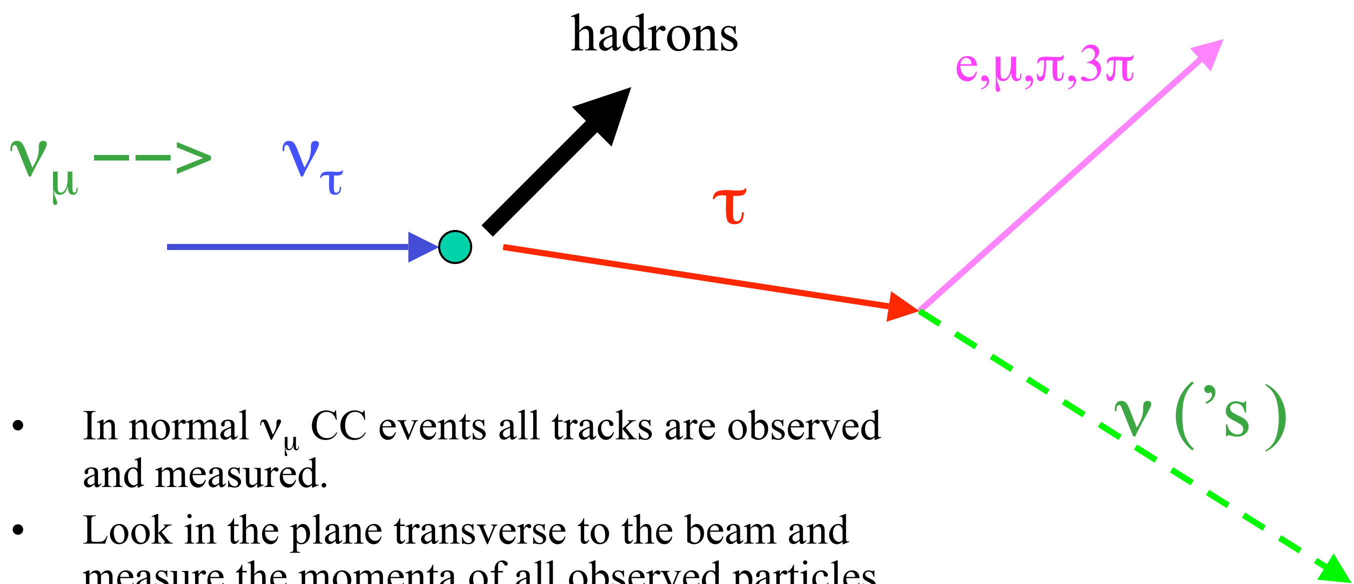




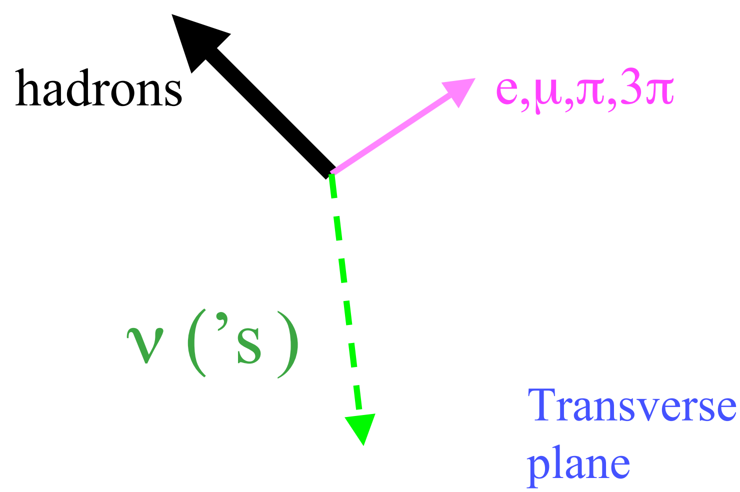
- Normal ν_μ CC events will have straight tracks attached to the interaction vertex
- The τ has a lifetime of **10^{-15} sec**.
- At these energies (a few GeV)
- It travels **~ 1 mm**
- Look for events with
  - a vertex,
  - a track coming out of it
  - **a kink in the track or a secondary vertex** after a finite path.
- Use detectors with excellent spatial resolution
- **Photographic emulsion** as a target



Two methods to detect a τ : Nomad

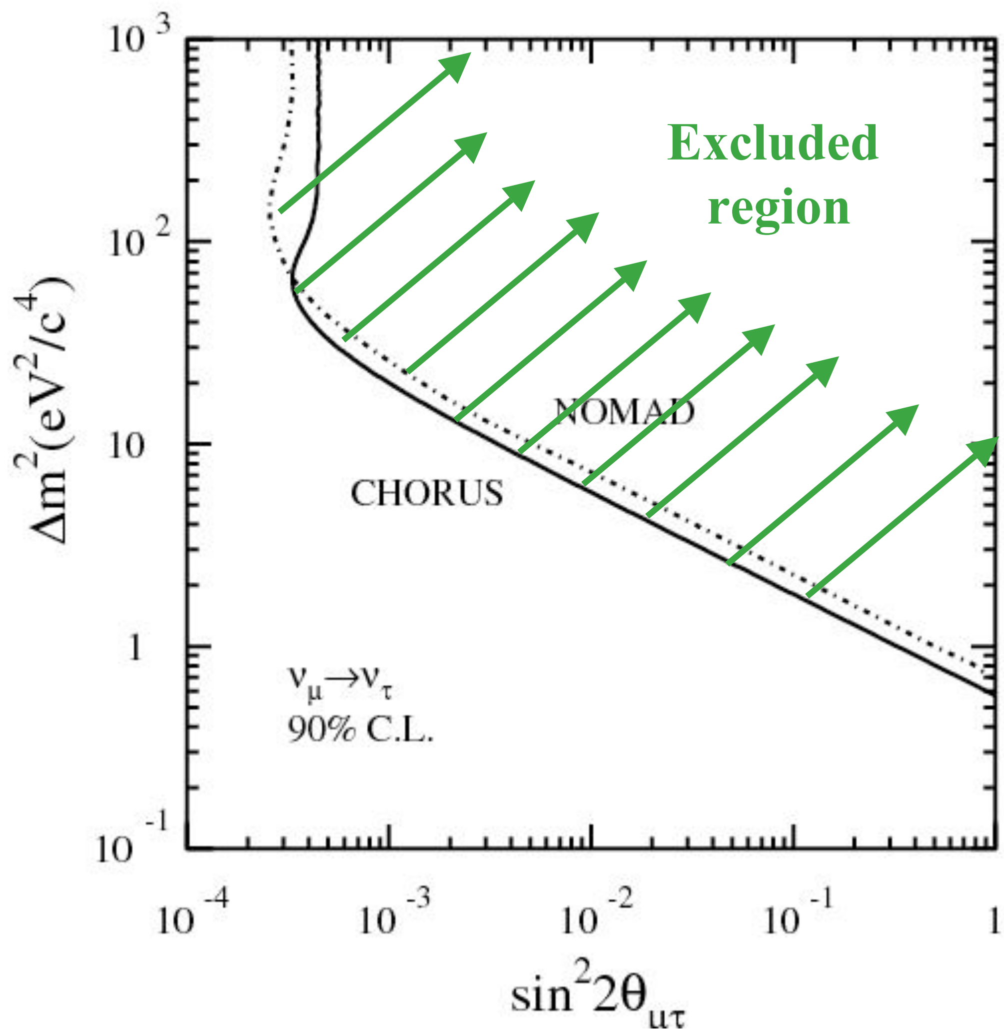


- In normal ν_μ CC events all tracks are observed and measured.
- Look in the plane transverse to the beam and measure the momenta of all observed particles in that plane: transverse momentum.
- Since the incident neutrino was perpendicular to that plane and the target nucleon was at rest,
  before interaction **$\sum$ Ptransv = 0**
- After interaction, "normal" ν_μ events $\sum$ Ptransv of all produced particles:
  $\sum$Ptransv = 0
- The τ can decay to e ν_e ν_τ, or μ ν_μ ν_τ or π ν_τ or 3π ν_τ.
- In all cases: neutrinos in the final state
- These are not observed. **$\sum$Ptransv $\neq$ 0**



The exclusion plot

- ν_τ's were NOT observed
- ν_μ ---> ν_τ does **NOT** occur at this Δm



Discovery

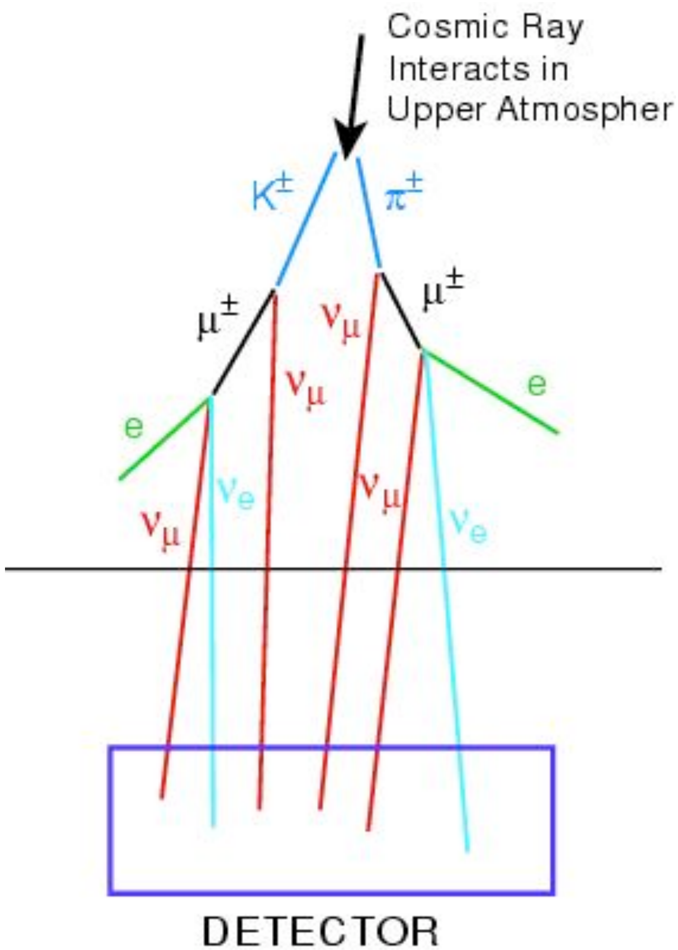
of

Oscillations

Atmospheric NEUTRINOS

Atmospheric Neutrinos: ν_e and ν_μ

Produced by π and K decays in upper atmosphere



- They decay to π, or K ---> $\mu + \nu_\mu$.
- Then the muons decay to e + $\nu_e + \nu_\mu$

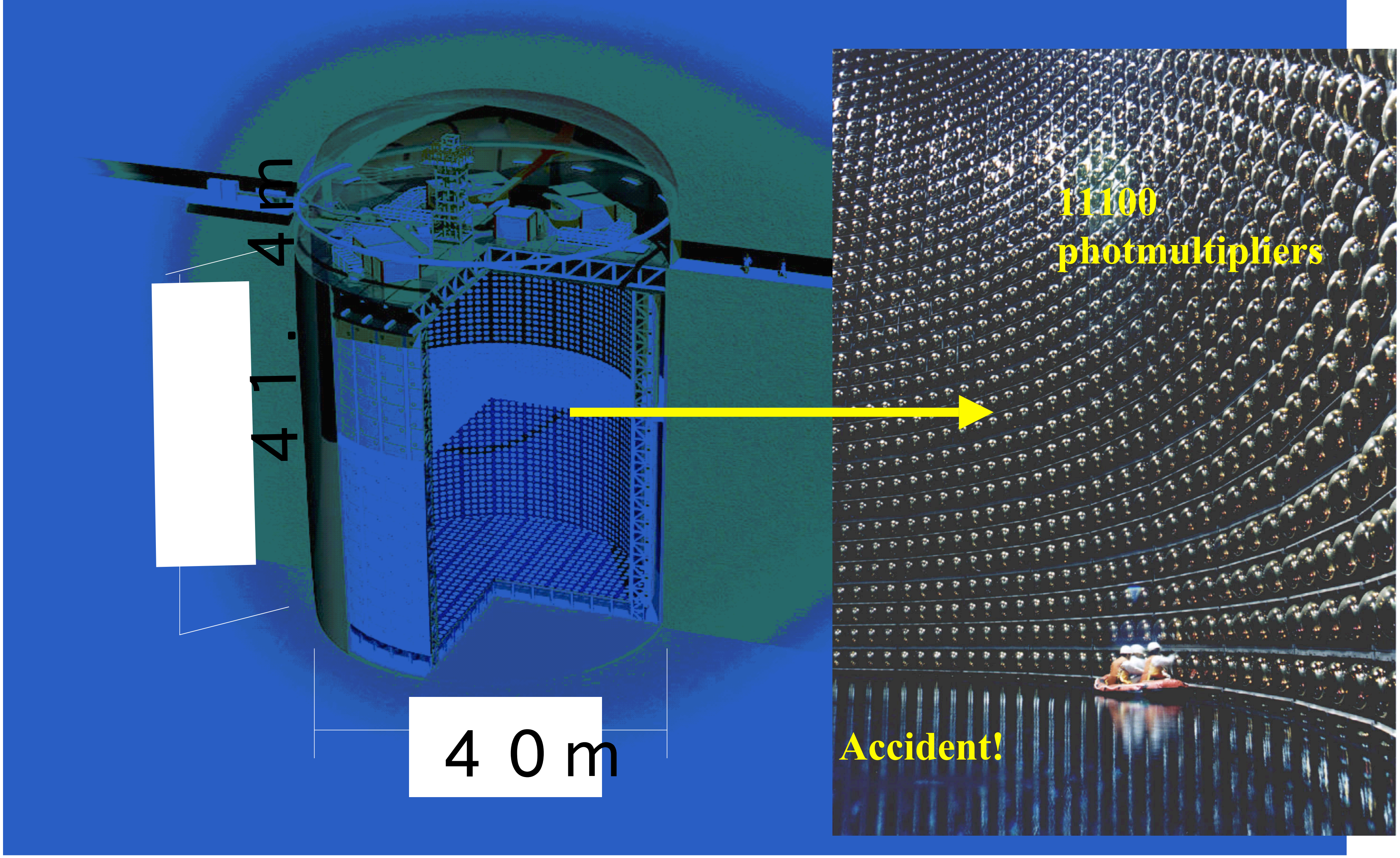
- $$\frac{\nu_\mu + \overline{\nu}_\mu}{\nu_e + \overline{\nu}_e}$$
- ratio should be = **2.**
- Measured to be **1** by some experiments. Why?
- Some others closer to 2.
- Inconclusive.
- Then SuperKamiokande was built.

Super-Kamiokande
The Detector

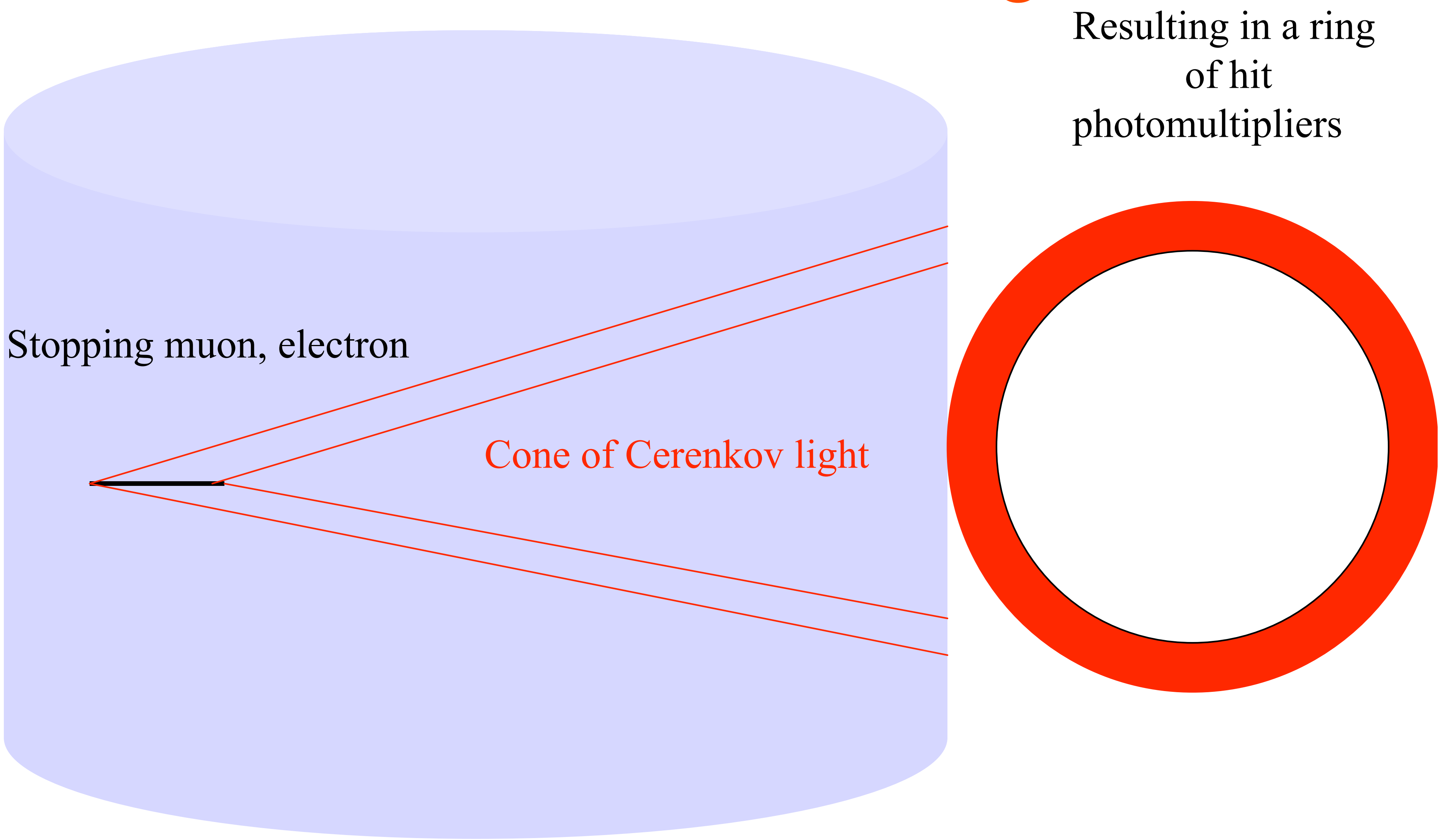
50000 tons ultra-pure water

22500 tons fiducial volume

1 km overburden = 2700 m.w.e.



How do we detect charged particles in water ? Cerenkov rings

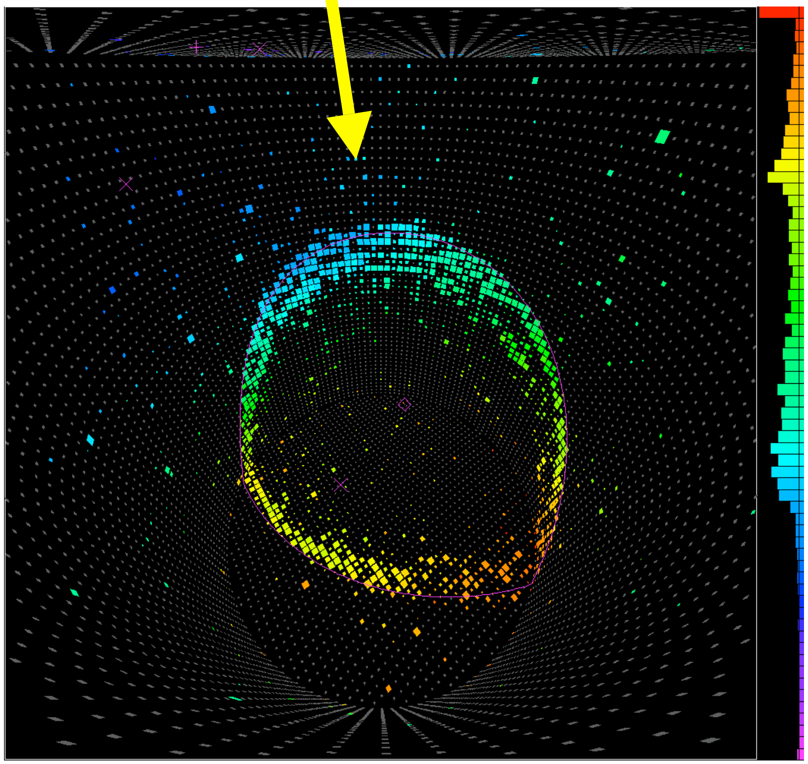


μ/e identification: Super-Kamiokande

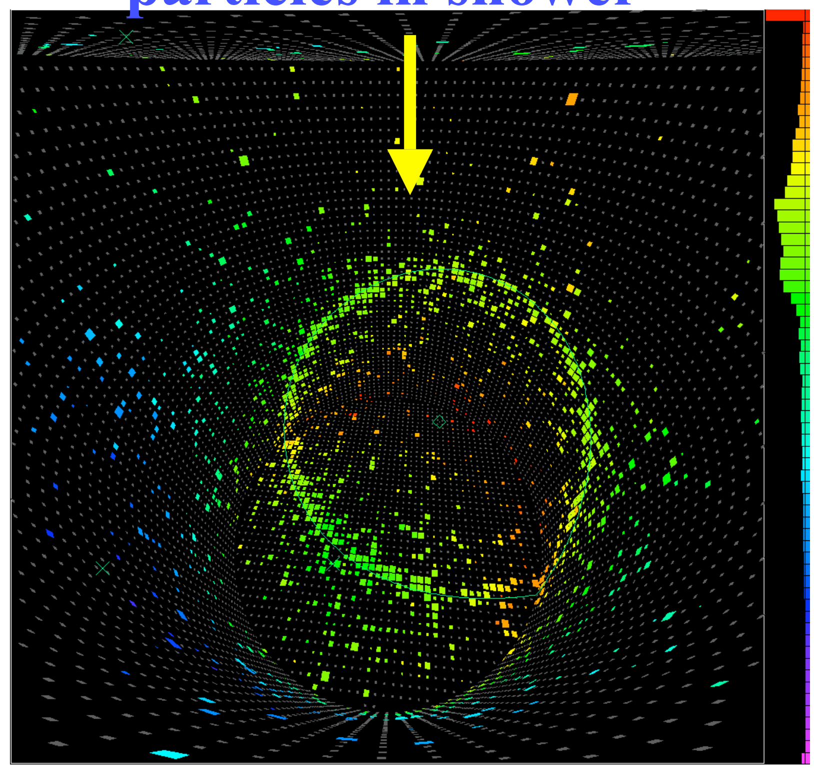
Detect through neutrinos through their charged current interactions.

$\nu_\mu X \rightarrow \mu + \ldots$ **$\nu_e X \rightarrow e + \ldots$**

μ sharp ring



e fuzzy ring due to many particles in shower

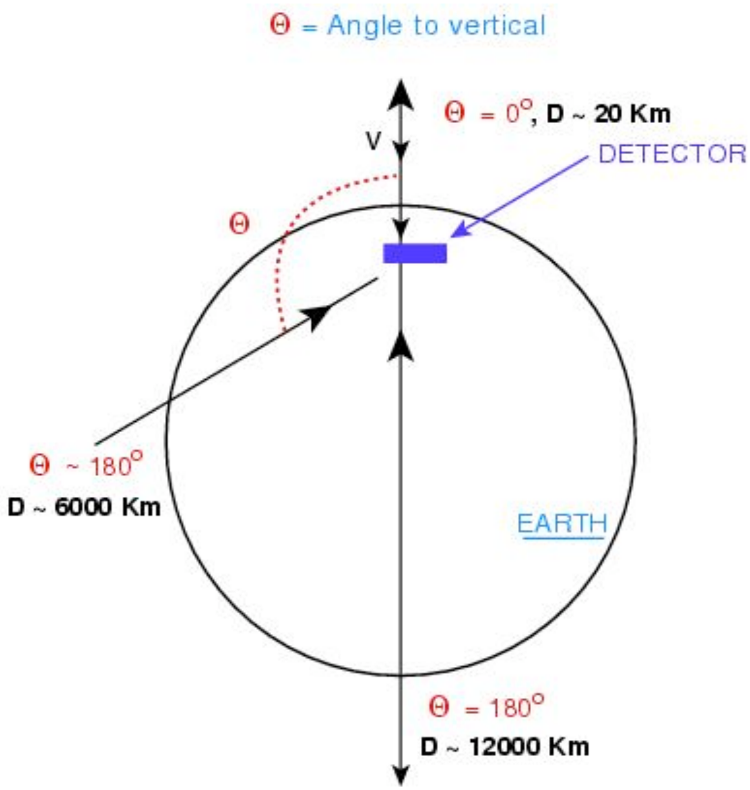


Vast improvement

Larger detector

Better statistics　　Better energy resolution　　Better directionality

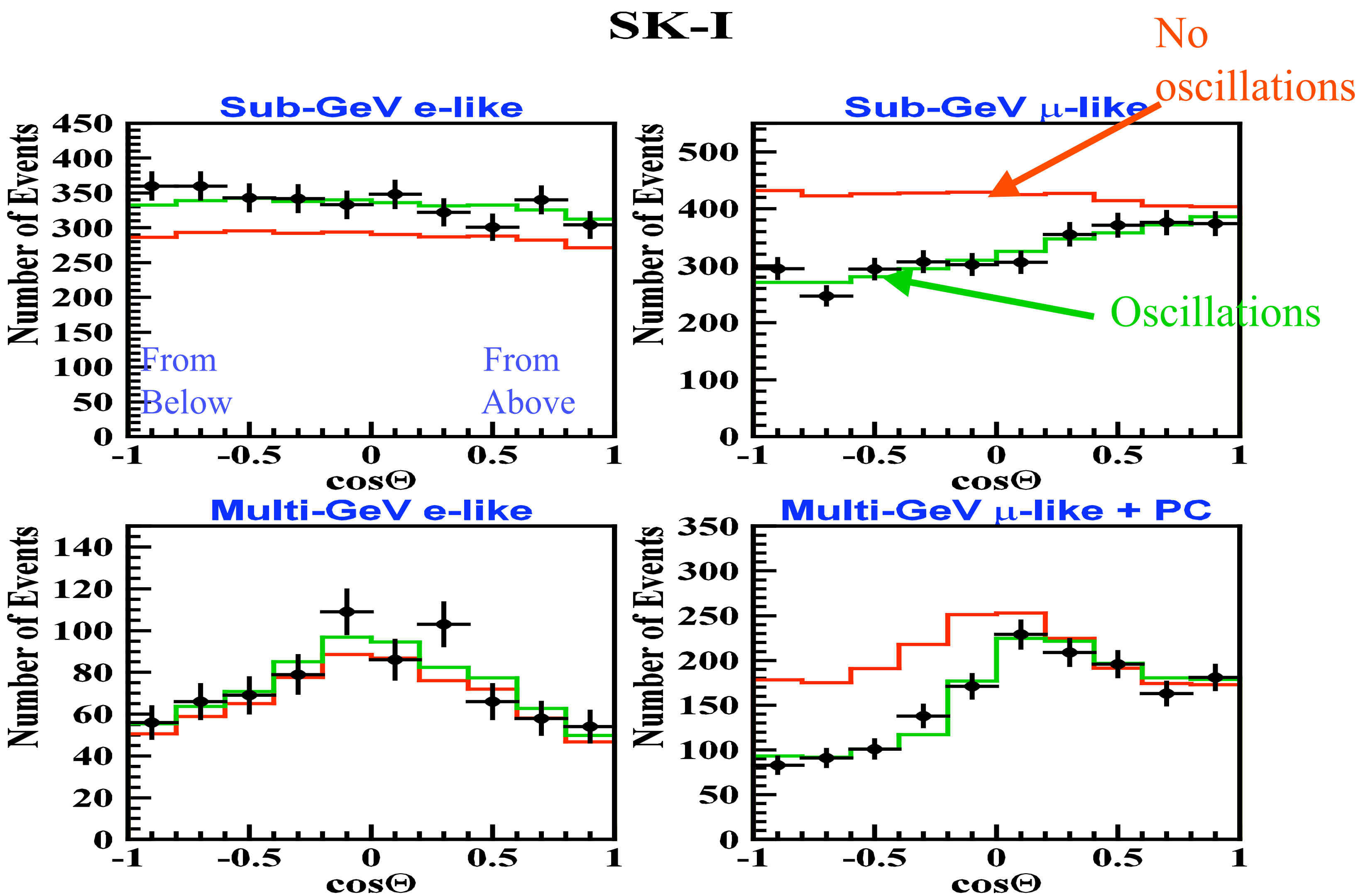
Could now determine
Incident direction
Of ν more accurately.
Direction - zenith angle



Directly related to
where the ν was produced
How far it traveled before
Being observed

Zenith angle --> BASELINE

Suppression of ν_μ zenith angle and energy dependent



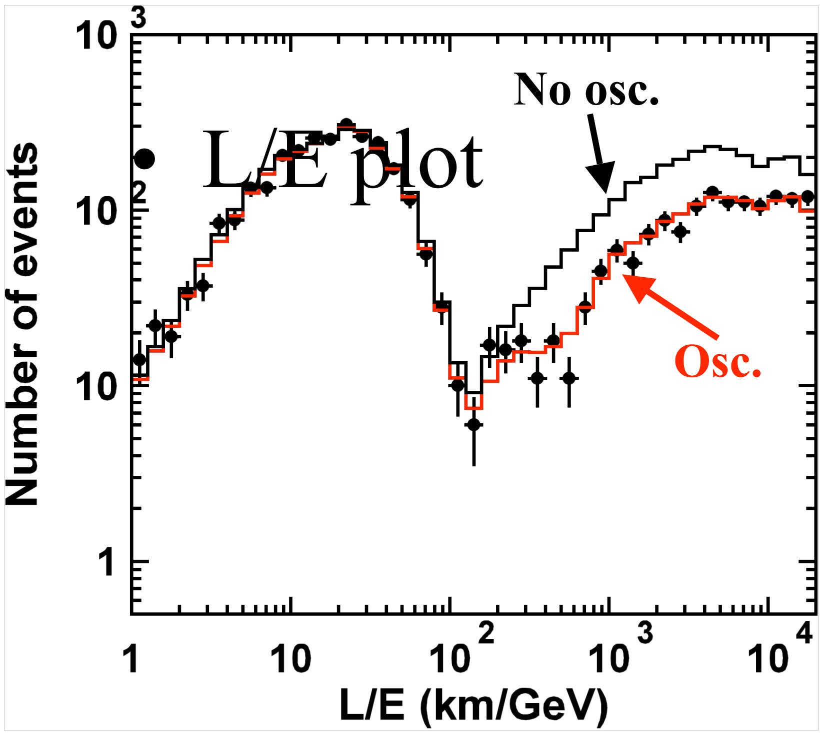
Suppression of ν_μ only. Not ν_e

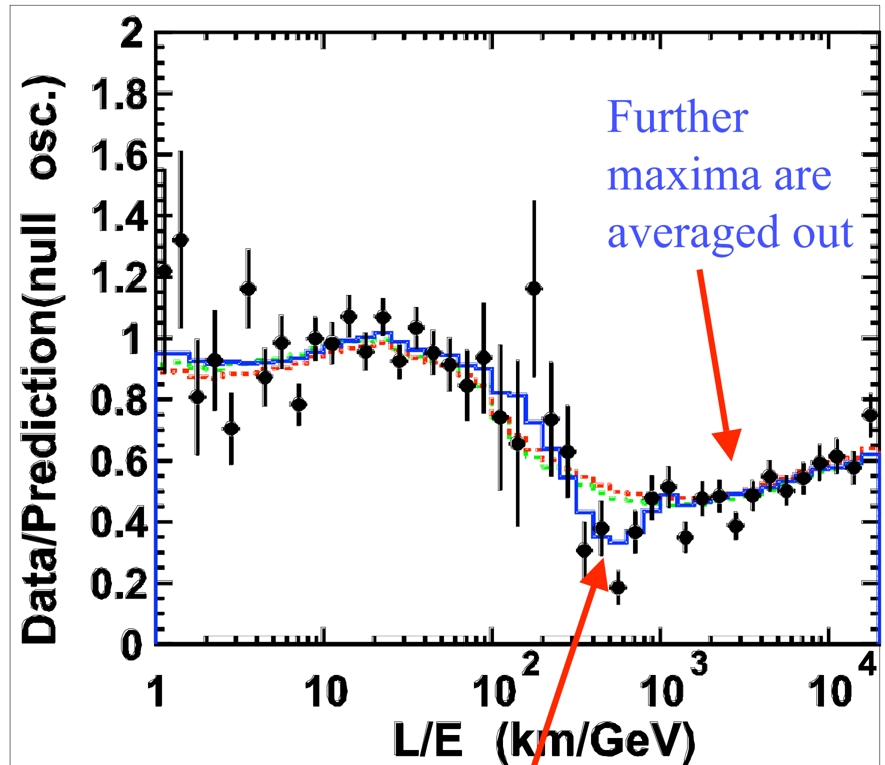
And only coming from below: with a long baseline.

First conclusive evidence for ν oscillations

Simulation programs: Monte Carlo

- L/E plot





Dip at first oscillation maximum

$1.9 \times 10^{-3} < \Delta m2 < 2.9 \times 10^{-3}$ eV^2

and

$\sin^2 2\theta > 0.92$

At 90% C.L.

What do they oscillate to? CHOOZ.

- Although ν_μ disappear, there is no corresponding excess of ν_e's.
- Probably **NOT** ν_μ ---> ν_e oscillation.
- Can we confirm this with "man-made" neutrinos?
- Maximum ν_μ suppression happens at L/E =

  L/E = (a few) x 1000km/(a few Gev) = 1000

- Reactors can probe: (a few) x km / (a few MeV)

- Same L/E -----> same Δm^2.

- CHOOZ experiment.

CHOOZ: A reactor experiment to measure θ_{13}

- Excellent source of **MeV antineutrinos.**

- If they oscillate to $\bar{\nu}_\mu$ or $\bar{\nu}_\tau$ they would **NOT** have enough energy to create **μ's** (106 MeV/c^2) or **τ's** (1777 MeV/c^2) via CC interactions.

- Cannot study oscillations through an **"appearance"** experiment.

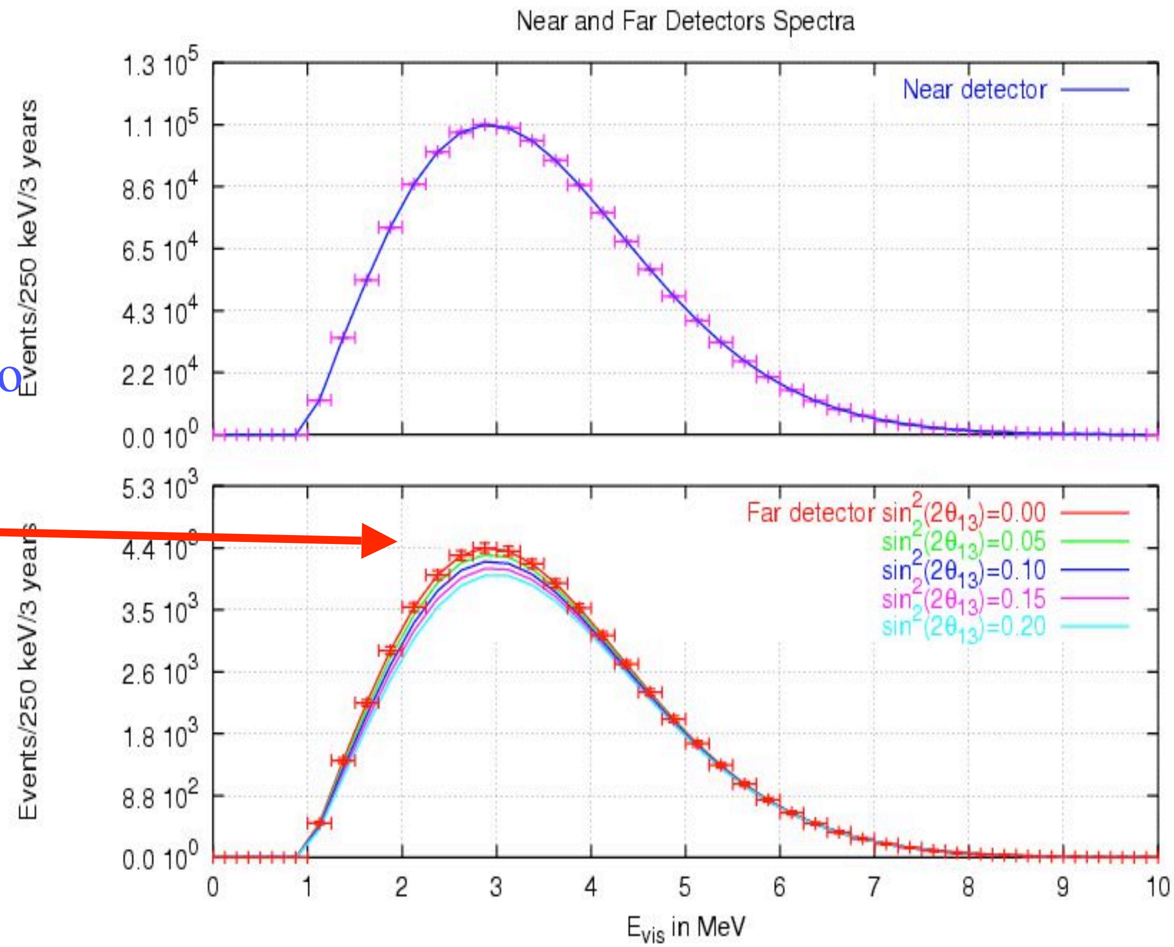
- Must study oscillations via **anti ν_e disappearance.**

$P_{ee} \sim 1 - \sin^2 2\theta_{13} \sin^2 [(\Delta m_{23}{}^2 L)/(4E_\nu)]$ Same Δm^2 as atmospheric.

- With a detector at 1 km, L/E = 1km/1MeV
  ~ same as atmospheric ~ 1000km/1GeV.

CHOOZ: A reactor experiment to measure θ_{13}

Distortion of the
$\bar{\nu}_e$ energy spectrum due to
Oscillation effects
are SMALL



Must know $\bar{\nu}_e$ energy spectrum very well to be able to claim a distortion
due to oscillations ---> control SYSTEMATICS
CHOOZ Systematic uncertainty: 2.7%
Mostly from flux and $\bar{\nu}$ cross sections

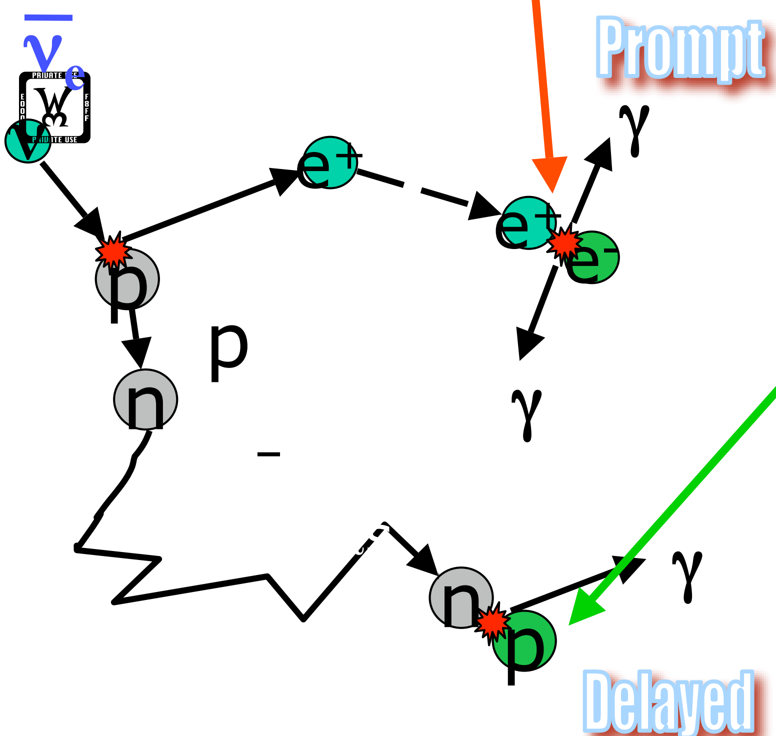
Technique

Measured 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.

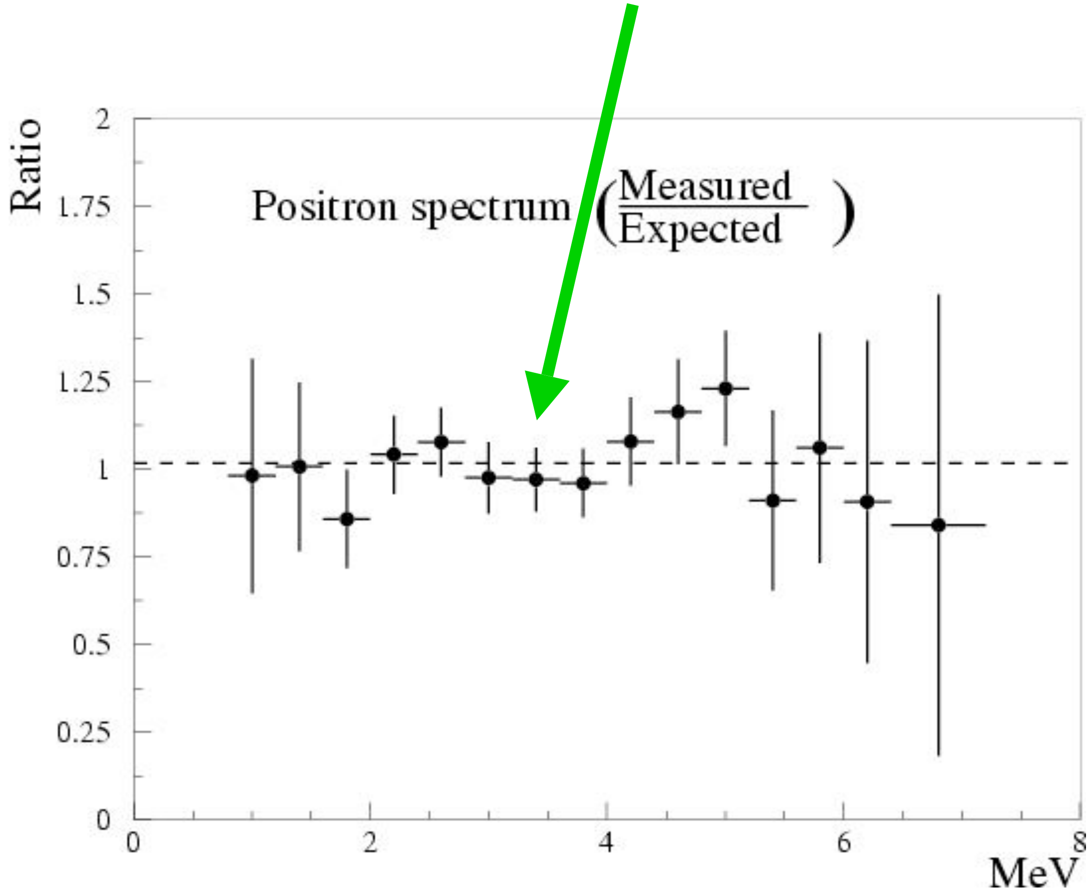
Delayed Coincidence
of 2 signals
Reduces background

CHOOZ: Limits on θ_{13}

Looked for distortions of the expected energy spectrum or in the rate

Did not find any.

Measured/Predicted(No oscillations) = 1.000±0.026



Set a limit on $\sin^2 2\theta_{13} < 0.12$

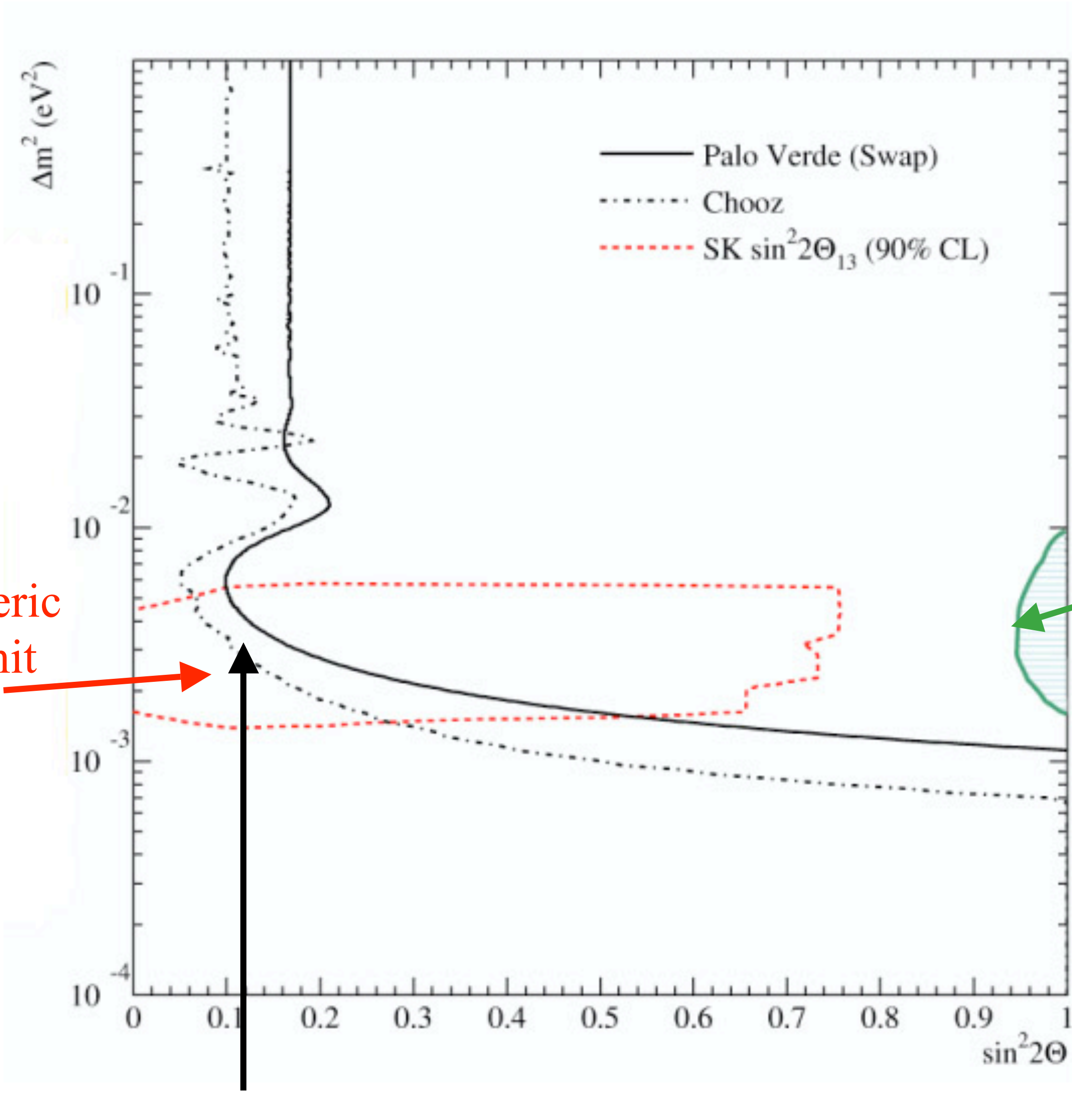
for $\Delta m^2_{atm} = 2.5 \times 10^{-3}\ eV^2$

or $\sin^2 \theta_{13} < 0.03$

Note: $\sin^2 2\theta_{13} = 4 \sin^2 \theta_{13}$

For small θ_{13} $\cos \theta_{13} \sim 1$

CHOOZ - Palo Verde limit



SuperK Atmospheric ν_e appearance limit

SuperK Atmospheric ν_μ disappearance

CHOOZ and PV limit If there is a ν_e disappearance it must be with sin2 $2\theta < 0.12$

Suppression of ν_μ in accelerator experiments: K2K, MINOS

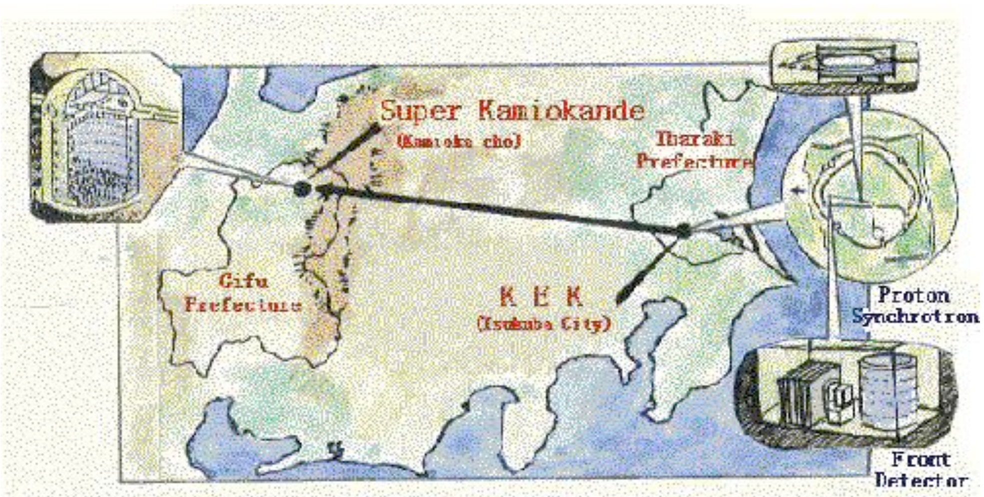
(confirmation of atmospheric result with "man-made" ν_μ's)

They look for ν_μ disappearance to observe oscillatory pattern in energy spectrum. Measure Δm^2 and θ_{23}

K2K 232 km E = 0.8 GeV
L/E = 290

MINOS (NUMI beam) 732km E = 2.5 GeV
L/E = 293

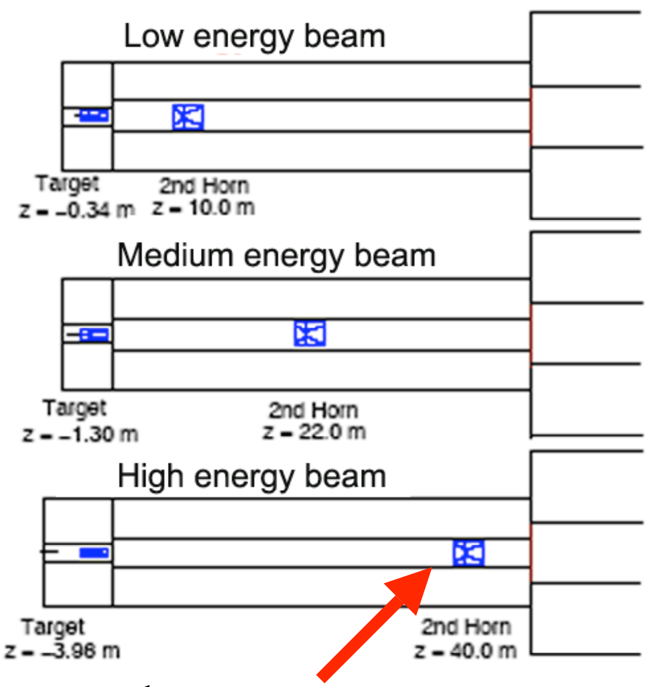
~ Same L/E as
Maximum ν_μ suppression
In atmospheric ~ 1000

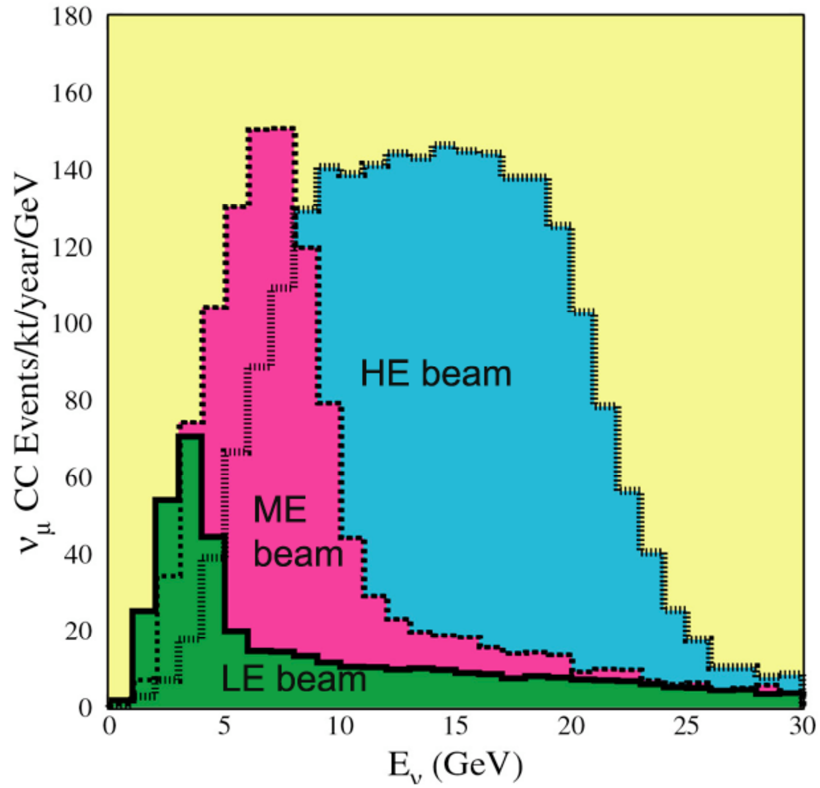


KEK to SuperKamiokande
Water Cerenkov Detector

Fermilab to Soudan Mine
Will concentrate on MINOS

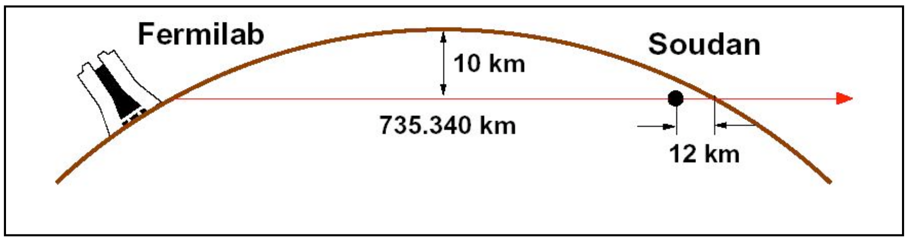
Neutrino beam



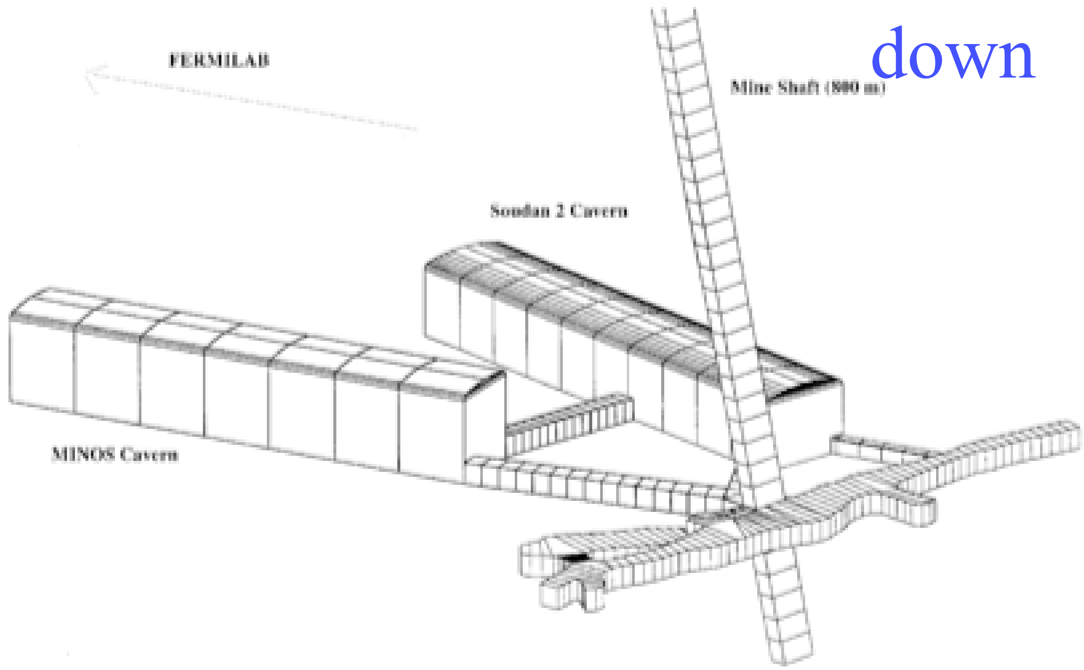


Move horn and target to change energy of Beam

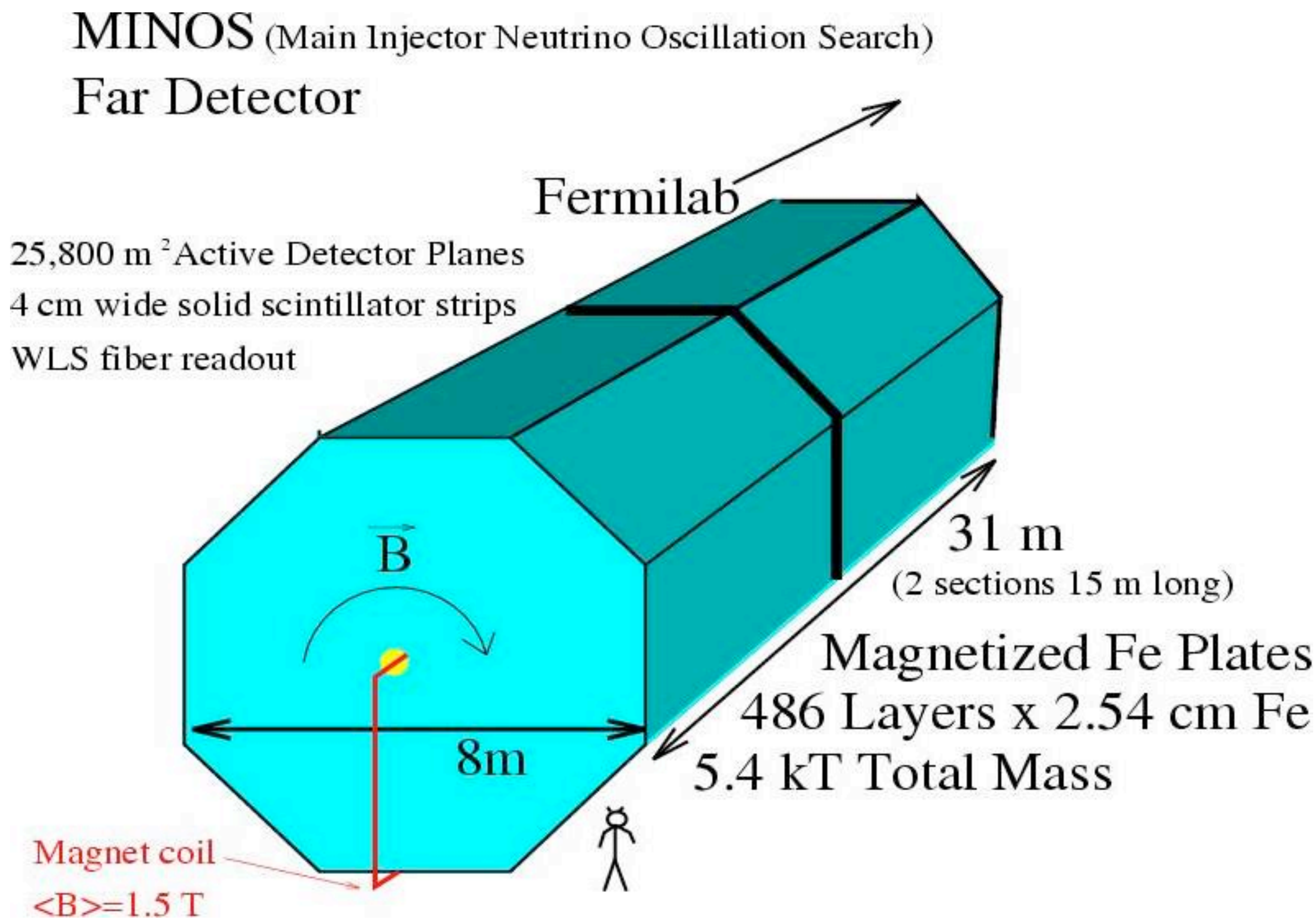
MINOS location: Mine



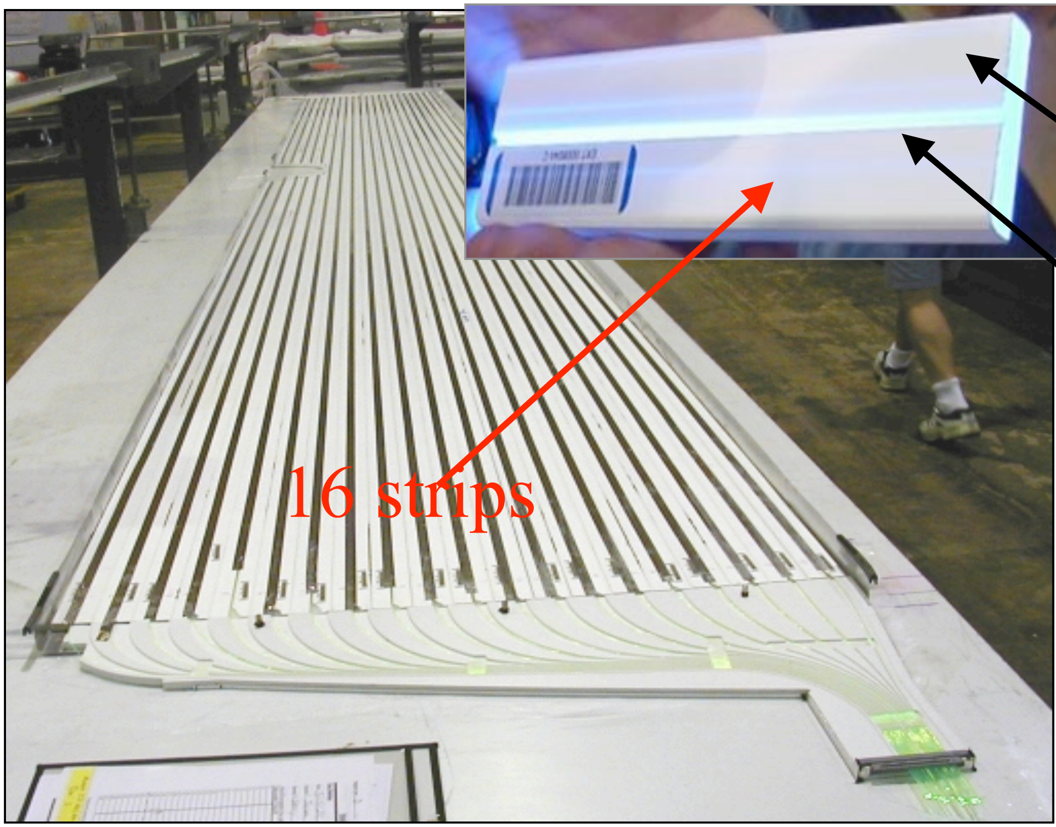
800 m
down



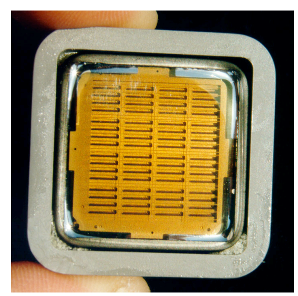
MINOS detector



MINOS scintillators



- Charged particle emits light in scintillator strip
- Travels to Wave Length Shifting fibre (WLS) in groove
- Absorbed and re-emitted isotropically at different wave length
- Travels down fibre
- Reaches photomultiplier (pmt)

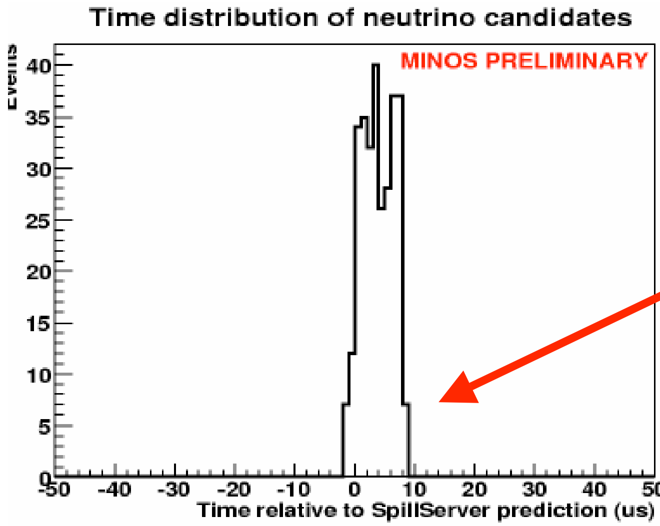


16 pixels per pmt
1 fibre/pixel

Near detector

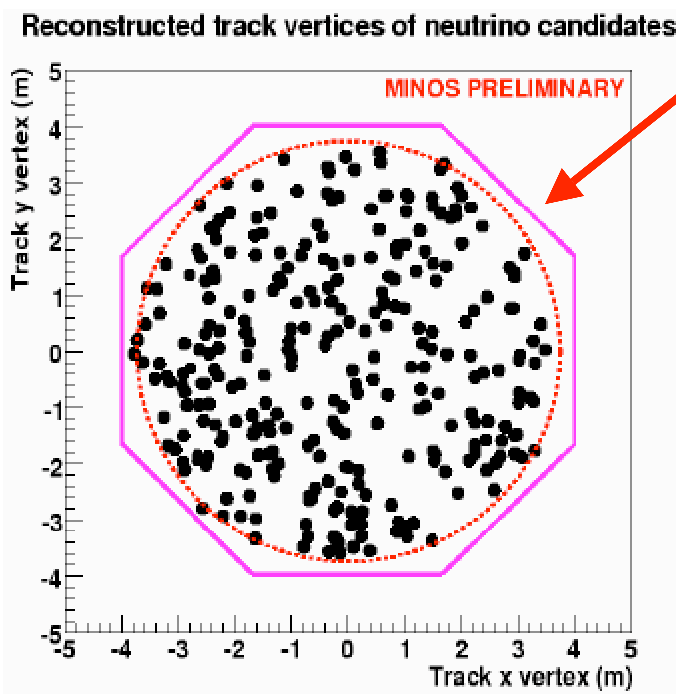
- To look for a disappearance signal, means looking for a distortion of the expected neutrino energy spectrum.
- This means that we must know **precisely** the shape of this spectrum.
- Can calculate it from simulation studies, but not easy.
  - Exact particle production cross sections at target
  - Exact material in beam line
- Better to measure it, before oscillations can occur
- Place a second, NEAR, detector in the beam line.

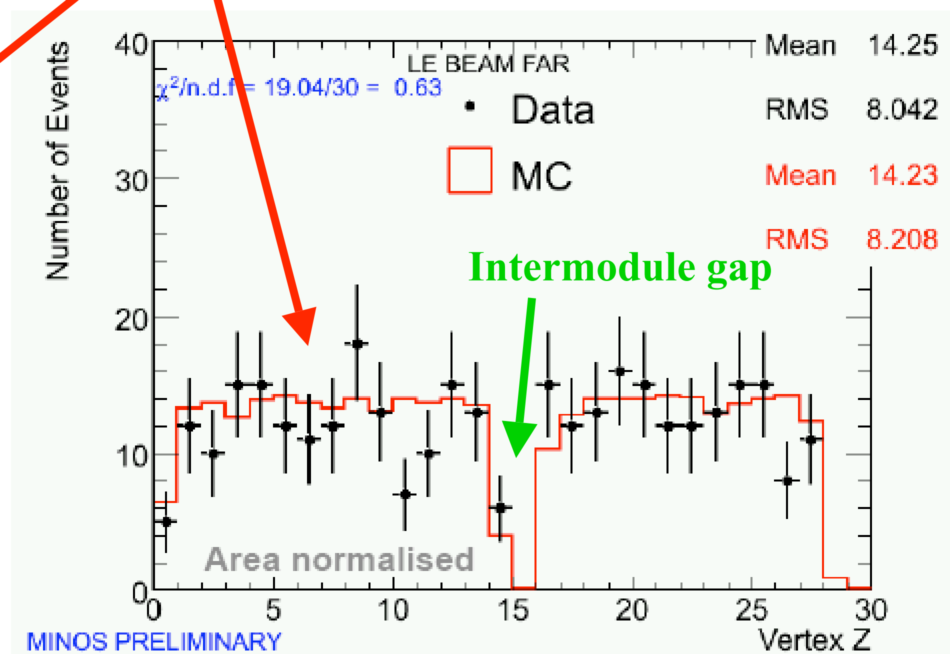
Far detector results I



In time with beam spill

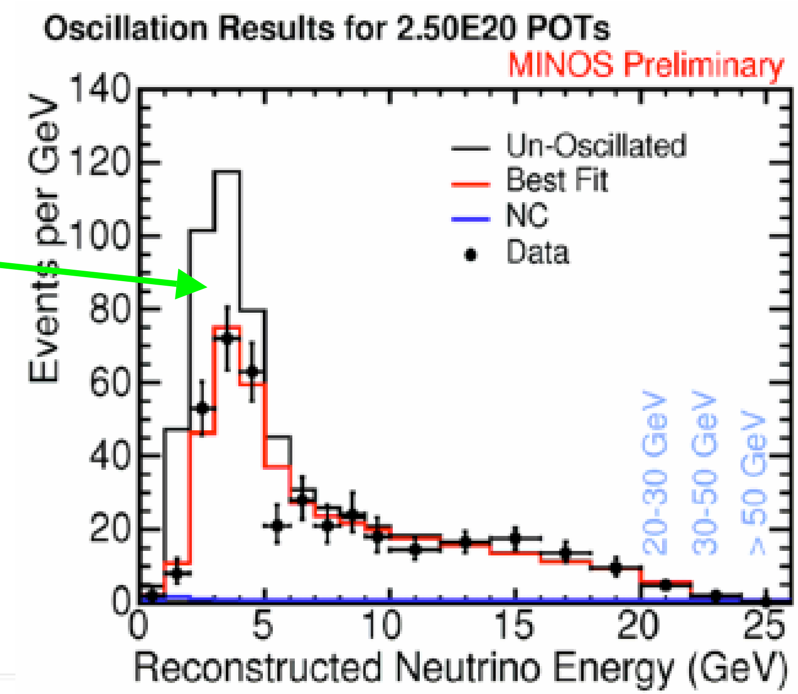
Uniform spatial distributions

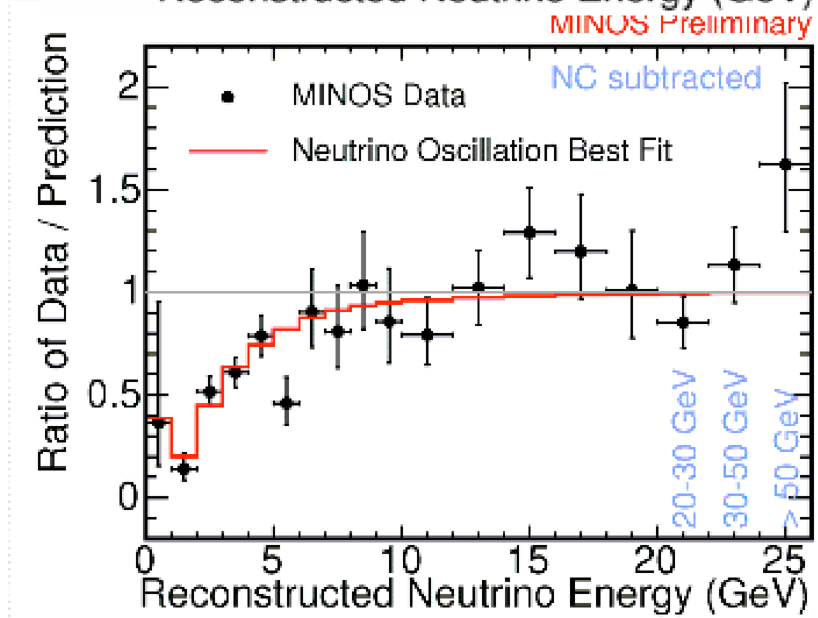




MINOS results

Suppression of events
at low energy



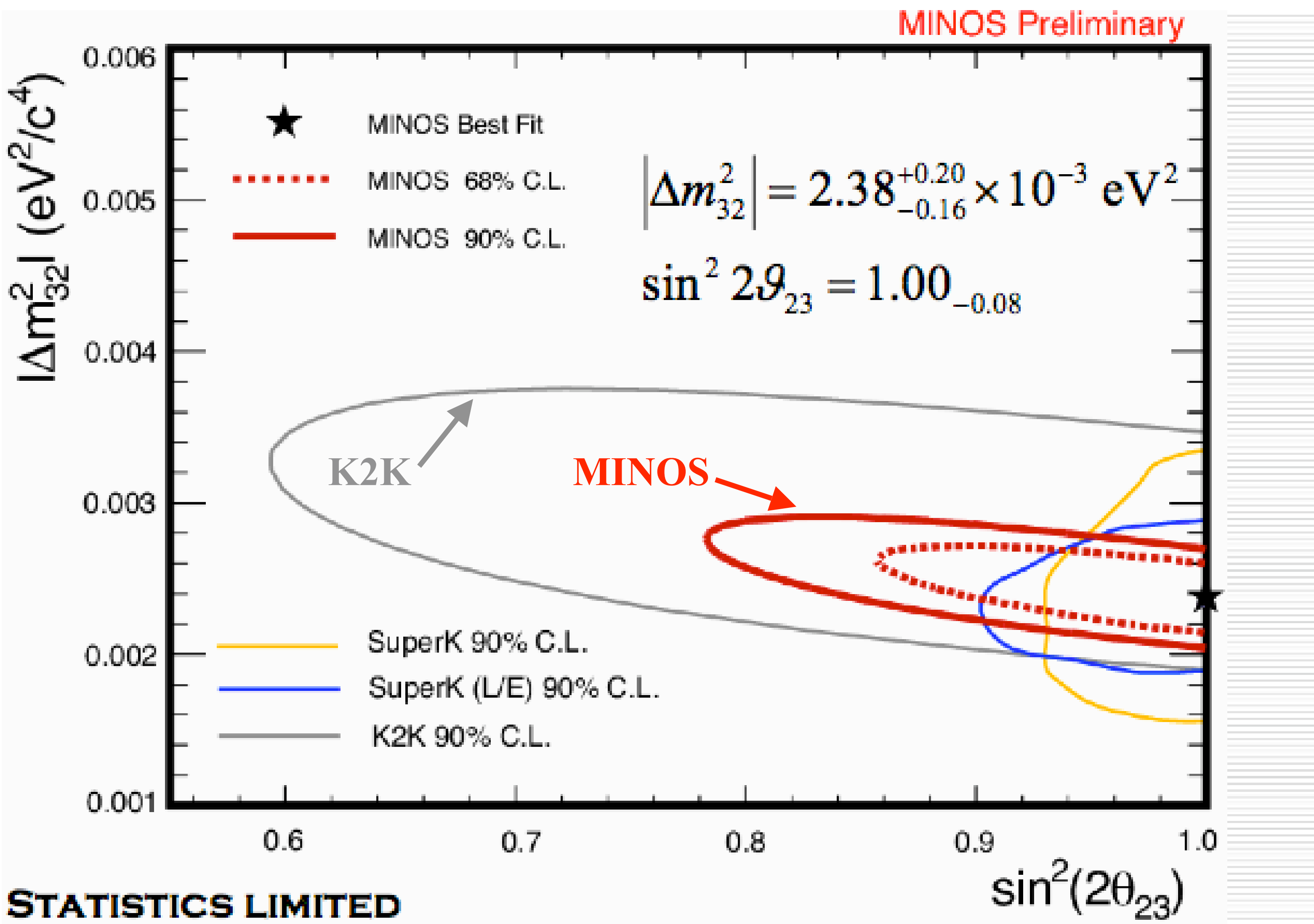


NO oscillation hypothesis χ^2/DOF = 3.9
Best oscillation hypothesis χ^2/DOF = 1.2

6.2 σ effect below 10 GeV

- Energy of maximum suppression --> Δm^2.
- Magnitude of suppression --> $\sin^2 2\theta_{23}$

K2K - MINOS Results



Future MINOS measurements

Present

We are here!