An Introduction to Modern Particle Physics

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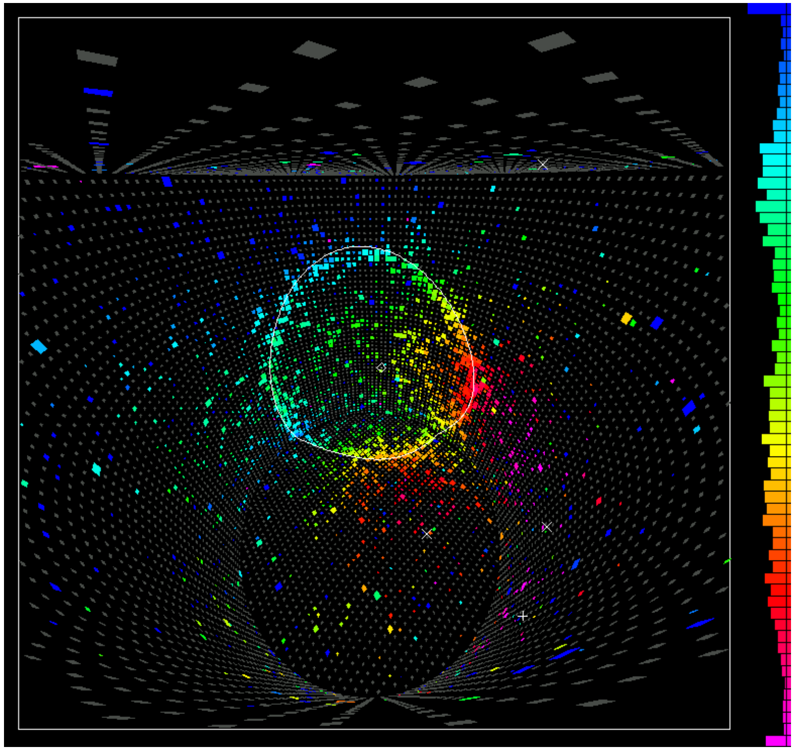


Science Summer School: 30th July - 1st August 2007

Course Synopsis

- ★ Introduction : Particles and Forces
  - what are the fundamental particles
  - what is a force
- ★The Electromagnetic Interaction
  - QED and e^+e^- annihilation
  - the Large Electron-Positron collider
- ★The Crazy world of the Strong Interaction
  - QCD, colour and gluons
  - the quarks
- ★The Weak interaction
  - W bosons
  - Neutrinos and Neutrino Oscillations
  - The MINOS Experiment
- ★ The Standard Model (what we know) and beyond
  - Electroweak Unification
  - the Z boson
  - the Higgs Boson
  - Dark matter and supersymmetry
  - Unanswered questions

The Weak Interaction

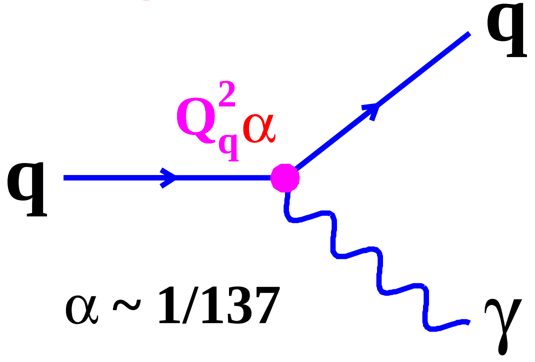
Electromagnetic Interaction:

★Mediated by massless photons

★Photon couples to ELECTRIC charge

★Does not change flavour

★QUARKS/CHARGED LEPTONS



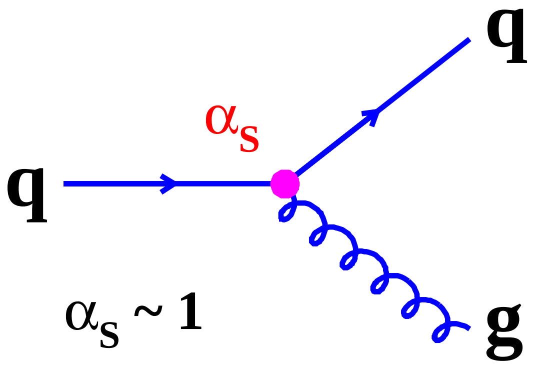
Strong Interaction:

★Mediated by massless GLUONS

★GLUON couples to “COLOUR” charge

★Does not change flavour

★QUARKS/GLUONS



Weak Interaction: IS VERY DIFFERENT

★Mediated by massive W BOSONS

★Couples to all particles equally

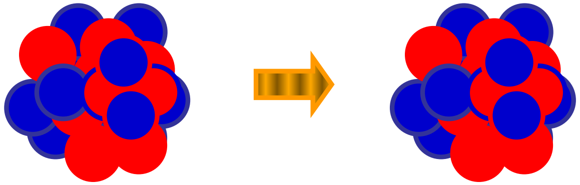
★Changes flavour

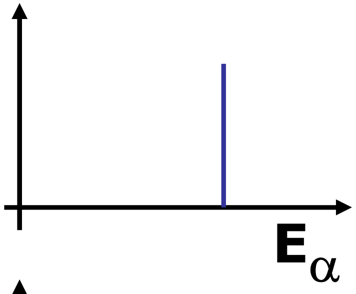
Historical Interlude

1900-1920s Nuclear Physics:

★ **3 types of nuclear radiation**

❶ **α decay**

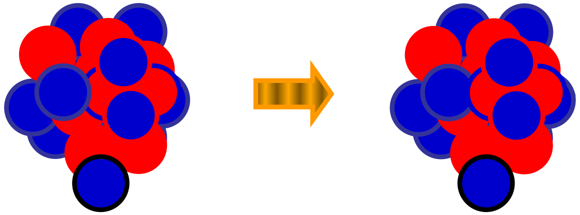


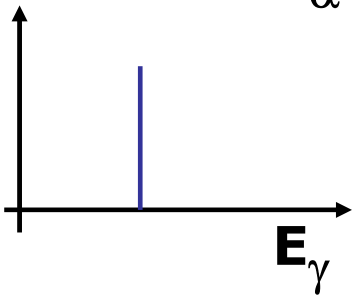


Nucleus emits He nucleus (alpha particle)

α always has same energy

❷ **γ decay**

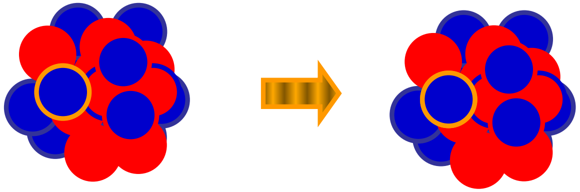


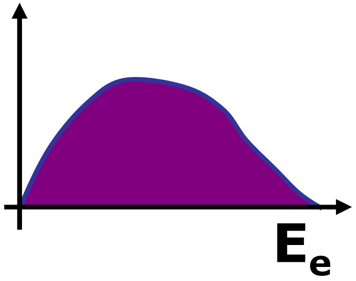


Nucleus emits a photon (γ)

α always has same energy

❸ **β decay**

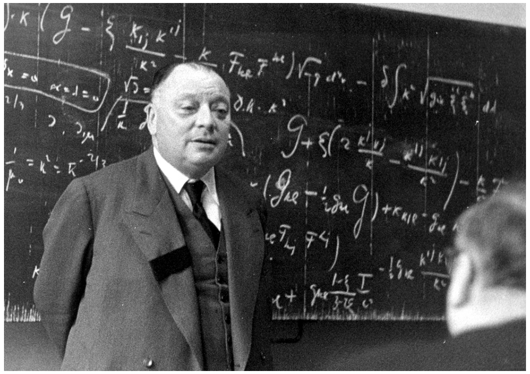




Neutron turns into a proton and emits a e^-

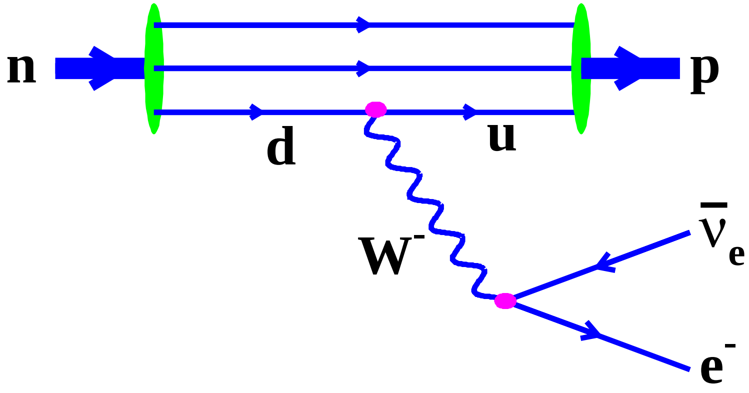
e^- emitted with a range of energies !

β decay and neutrinos



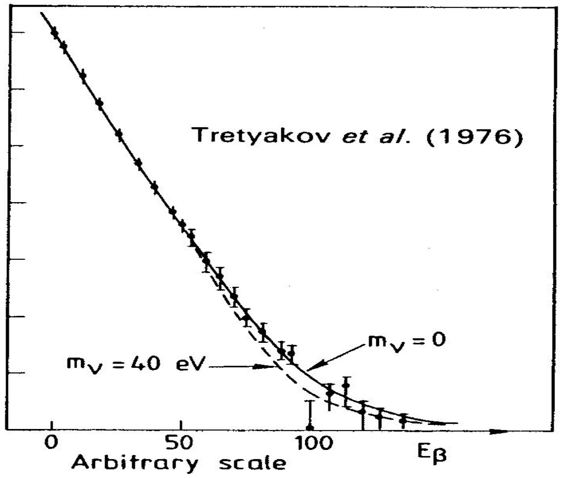
- ★In **1930** **Pauli** proposed that a new unobserved particle, "the neutrino" was emitted with the **e⁻** in β decay
- ★The neutrino, ν, had to be **neutral** and **WEAKLY interacting** – it hadn't been detected !

- Neutrinos were first detected in **1956**
- ★We now understand b decay in terms of the **WEAK** force which is mediated by a **MASSIVE** (**80 GeV/c²**) **W-boson**



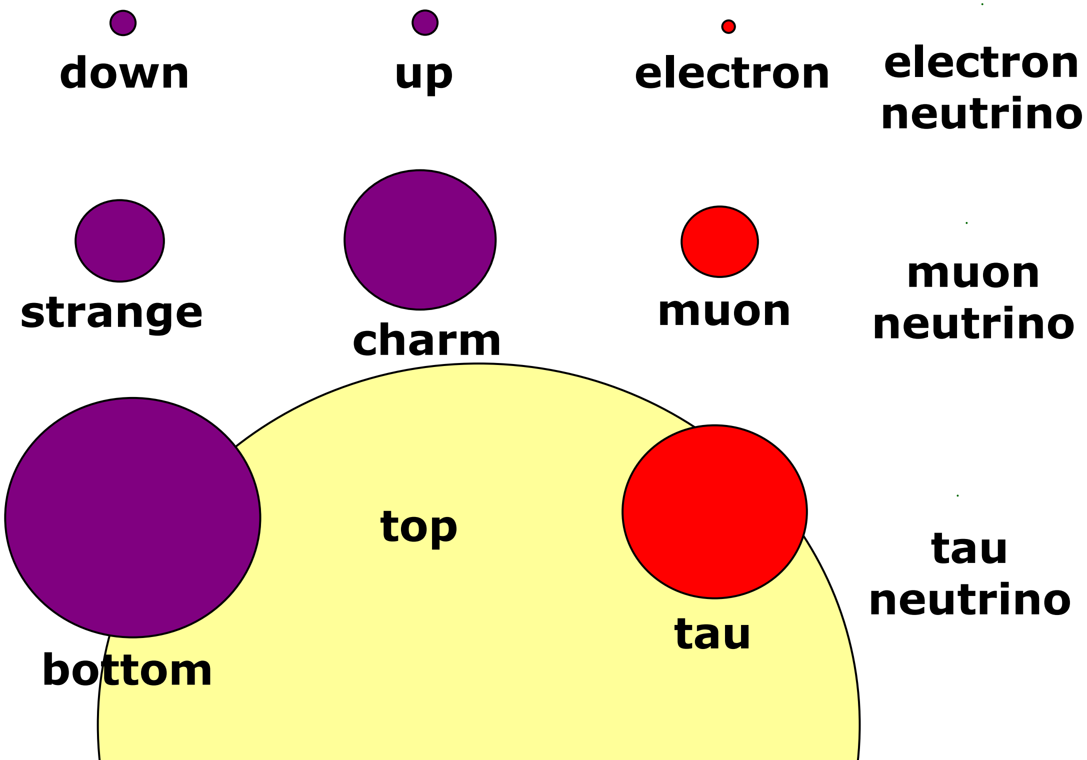
- ★Here the weak interaction vertex changes a **d → u** quark and then "pair-produces" an **e⁻** and a ν_e

Neutrino Mass



- ★by looking at the β decay spectrum can try to determine n mass
- ★a ν mass would change e$^-$ spectrum
- ★no change seen

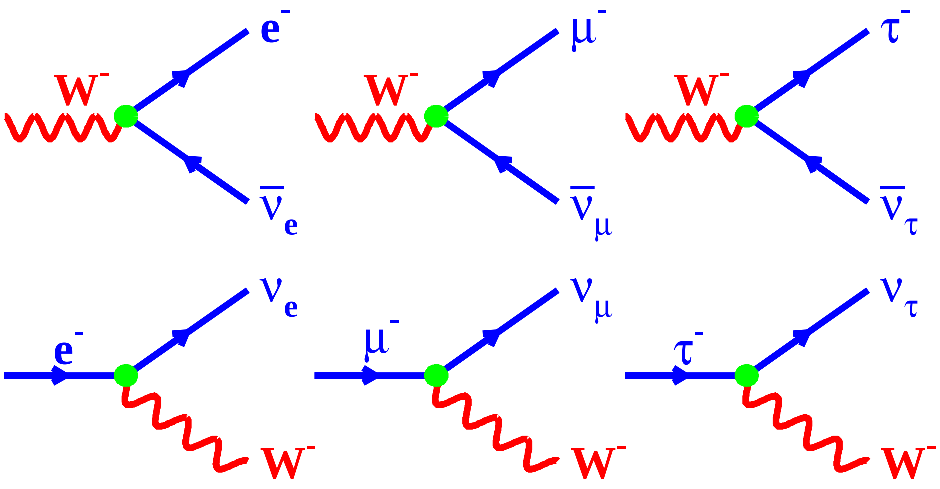
ν_e mass < $3\mathrm{x}10^{-9}$ GeV/c^2 (Very Small)



Neutrino masses so very small that for a long time assumed to be 0

Leptonic Weak Interaction Vertices

★ **First consider leptonic WEAK interactions**

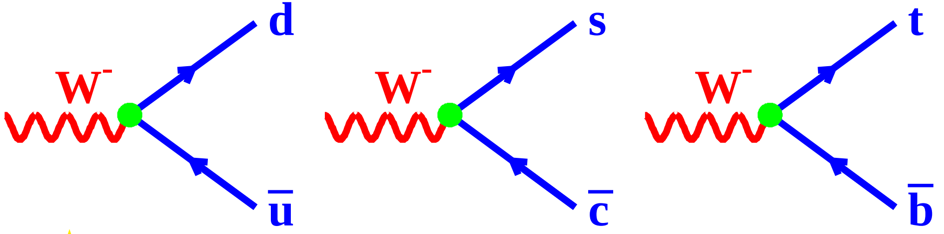


- ★ **The W bosons are charged, i.e. W^+, W^-**
- ★ **The W boson couples a charged lepton with ITS neutrino:**

  $e^- \leftrightarrow \nu_e \quad \mu^- \leftrightarrow \nu_\mu \quad \tau^- \leftrightarrow \nu_\tau$

- ★ **A similar picture for quarks. W bosons couple a charge 2/3 quark (u,c,t) with a charge 1/3 quark (d,s,b)**

e.g.

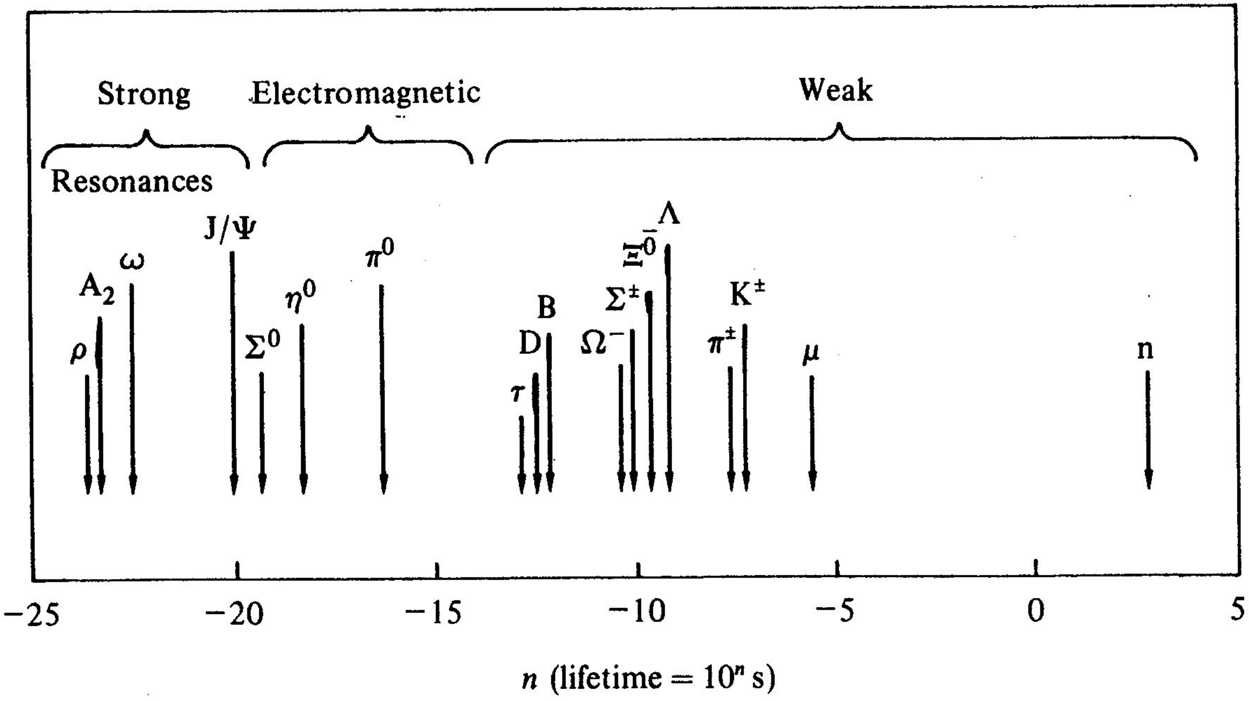


The weak interaction strength is UNIVERSAL: same "weak charge" for all particles involved

Weak decays

- **Because the WEAK interaction changes flavour it is responsible for the majority of particle decays**

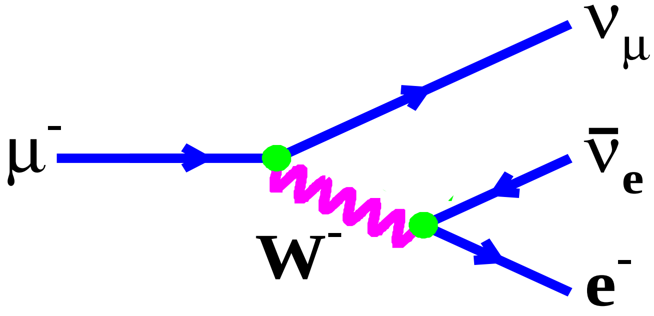
e.g.



- **Because the WEAK interaction is a WEAK force particle lifetimes are relatively long.**

e.g. Muon decay

e.g. The muon is a fundamental particle (heavy version of the electron $m_\mu \approx 200\, m_e$). Without the WEAK interaction it would be stable. However, because, the WEAK force changes flavour the muon can decay to (the less massive) electron



Problem: draw Feynman diagrams for tau decay to i) an electron, ii) a muon, and iii) to pion (u$\underline{d}$ meson)

What are the relative decay rates ?
(universal force + remember colour)

How Weak is Weak ?

RECALL:

EM Force between two electrons:

- ★ **$1x10^{-15}$ m apart : 200 N (equivalent weight of small child)**

STRONG Force between two quarks:

- ★ **$1x10^{-15}$ m apart : 160000 N (weight of large elephant)**

- **WEAK Force between an electron and a neutrino:**
  - **$1x10^{-15}$ m apart : 0.002 N (weight of grain of sand)**

- ★ **Neutrinos can only interact via weak force although ~$1x10^{15}$ ν/second pass through each of us, only ~1/lifetime will interact !**
- ★ **How much lead required to stop a 1 MeV particle ?**

• **p**	**require**	**0.1 mm of lead**	**STRONG**
• **e^-**	**require**	**10 mm of lead**	**EM**
• ν	**require**	**10 light years of lead**	**WEAK**

(1 MeV is the typical energy released in nuclear decays)

★Two interesting questions...........

What do we know about neutrinos – are they really massless ?

Why is the weak force so much “weaker” than the EM and Strong forces ?

Discuss neutrinos first.....

Neutrinos are Everywhere

- ~330 ν in every cm^3 of the universe – but very low energy (Cosmic Neutrino Background)
- Nuclear reactions in the sun emit 10^{38} ν per second
- Natural radioactivity in the Earth (20 TW of power in ν)
- Nuclear power plants ⇨ 10^{21} ν per second
- Each of you contains ~20 mg of ^{40}K ⇨ emit 300,000,000 ν per day
- Cosmic rays hitting the Earth's atmosphere

BUT VERY HARD TO DETECT

Detecting Neutrinos

- Because ν only interact weakly need **extremely large detectors + intense sources** to have a chance of detecting neutrinos

★ The neutrino sources are free ! e.g.
  - Solar neutrinos
  - Atmospheric Neutrinos

★ To build an extremely large detector ➡
$$$$, ££££, €€€€, ¥¥¥¥

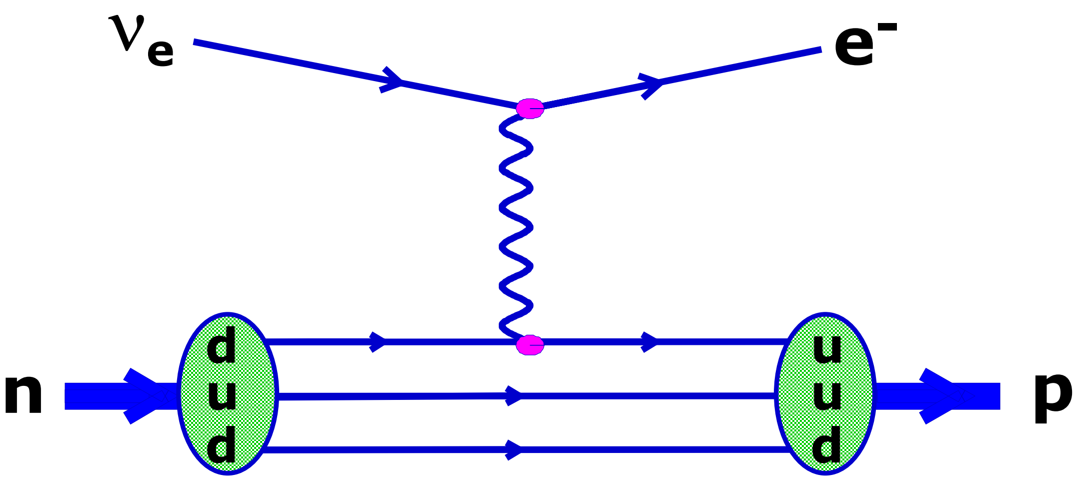
★ Need a very cheap way of detecting neutrinos

WATER

Water as a Neutrino Detector

NOTE: can never see the neutrinos directly

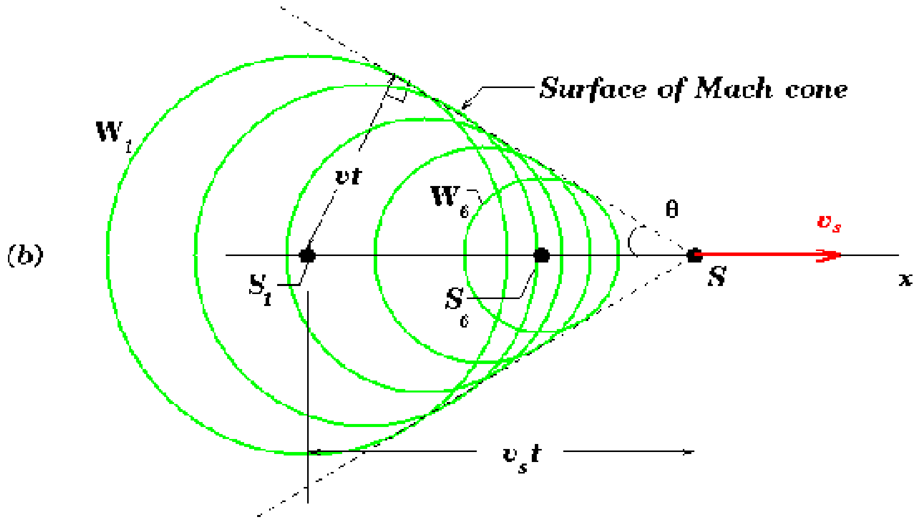
- ★ Neutrinos only interact **WEAKLY** and when (if) they do they "turn into" charged leptons (+see later for Z)
- ★ Detect **NEUTRINOS** by observing the charged lepton



- ★ A neutrino (CC) interaction produces an relativistic electron ($v \approx c$)

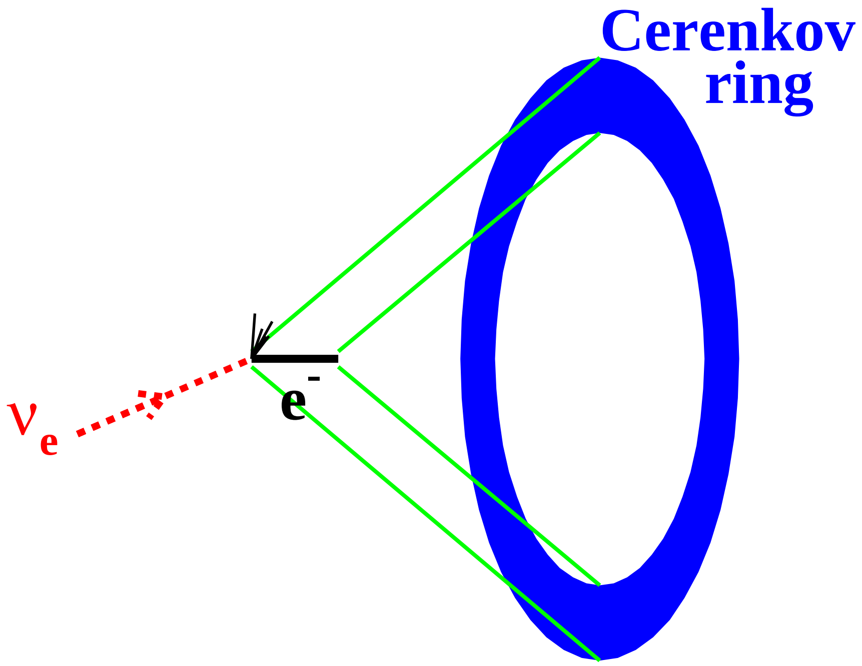
Čerenkov Radiation

- Detecting the electron in water
- When a particle travels faster than the velocity of light in the medium (c/n) it emits light at a fixed angle to the particles direction : "Čerenkov radiation"



- Source of "blue glow" seen around nuclear reactors

- ★ A particle produced in neutrino interactions will (typically) only travel a short distance.
- ★ it therefore produces a ring of Čerenkov light

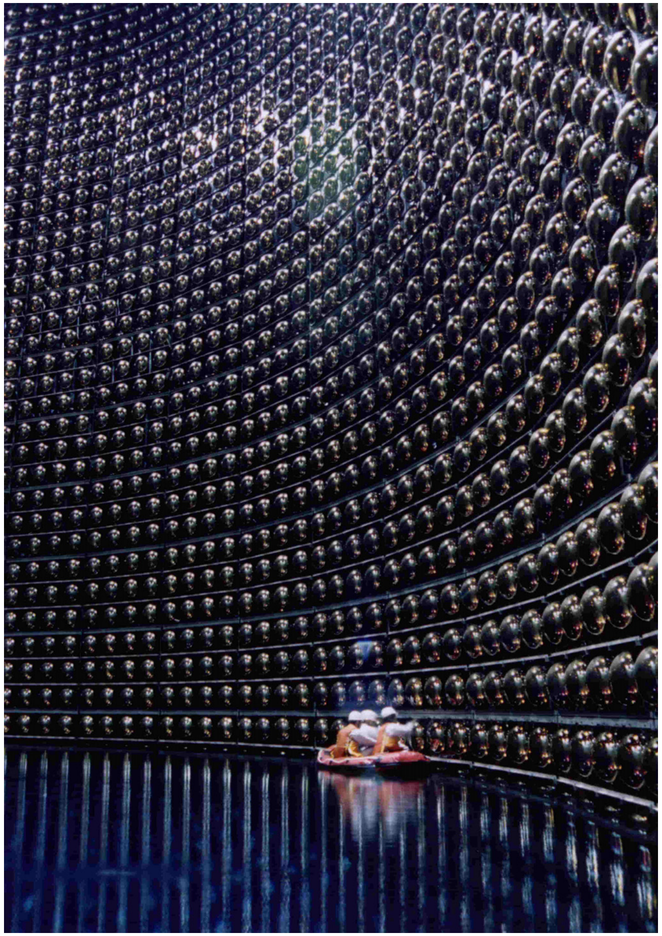


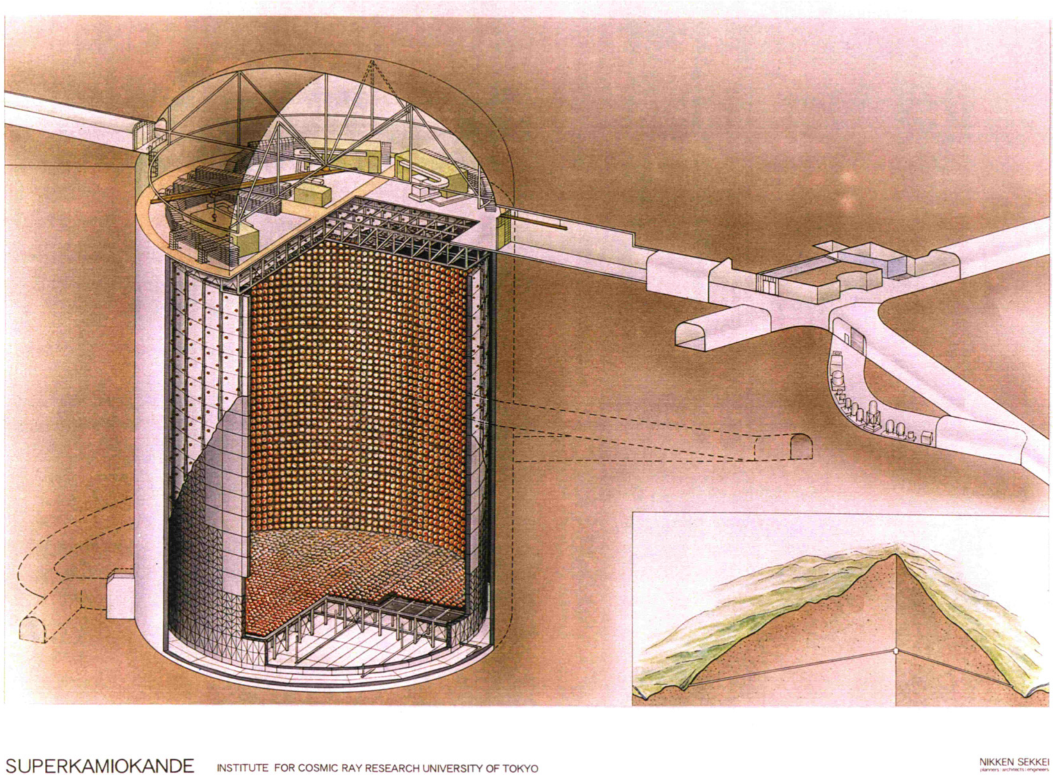
- ★ The light can be detected using photo-multiplier tubes (**PMTs**) - devices which can give an electrical signal for a single photon

Neutrino Detection

SUPER-KAMIOKANDE

- ★ A huge tank of water
- ★ 50000 tons H_20
- ★ viewed by 11246 PMTs

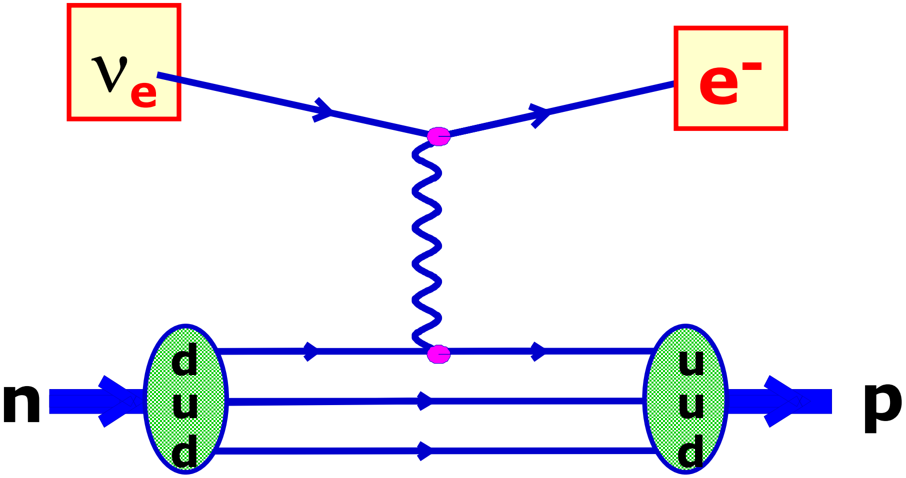


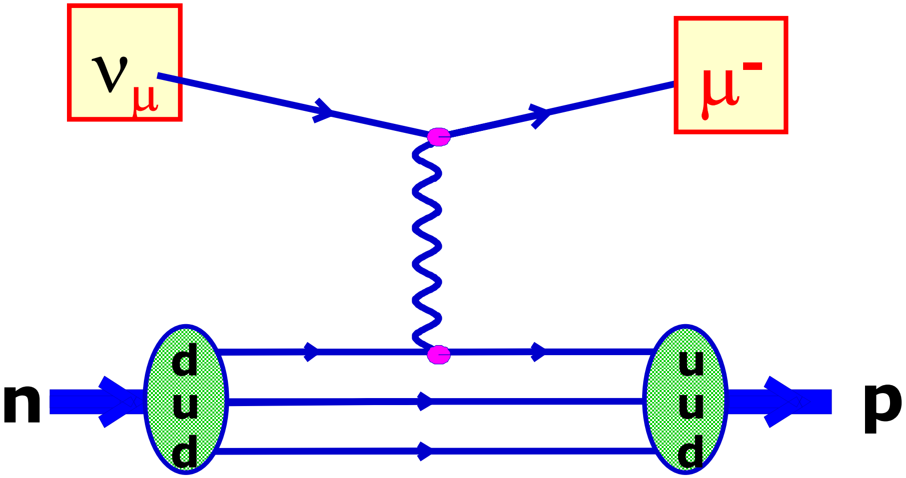


NOTE:

- **Different flavours of neutrinos produce the corresponding charged lepton flavour**

  e.g. $\nu_\mu \rightarrow \mu^-$



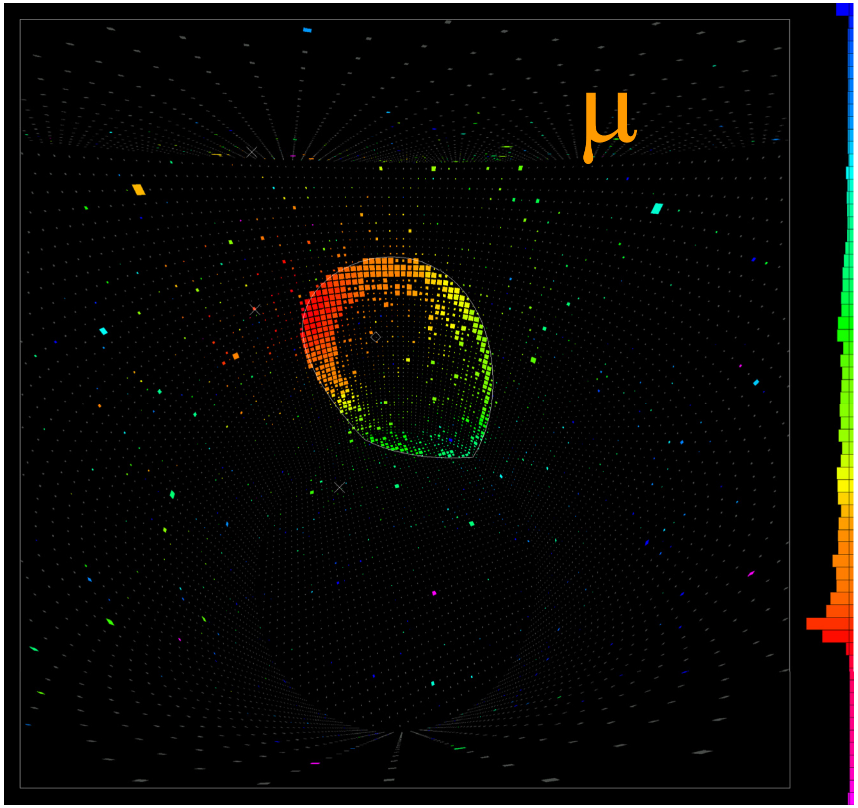


This is almost "by definition" – the ν_μ state is defined as that which couples to a W and μ^-

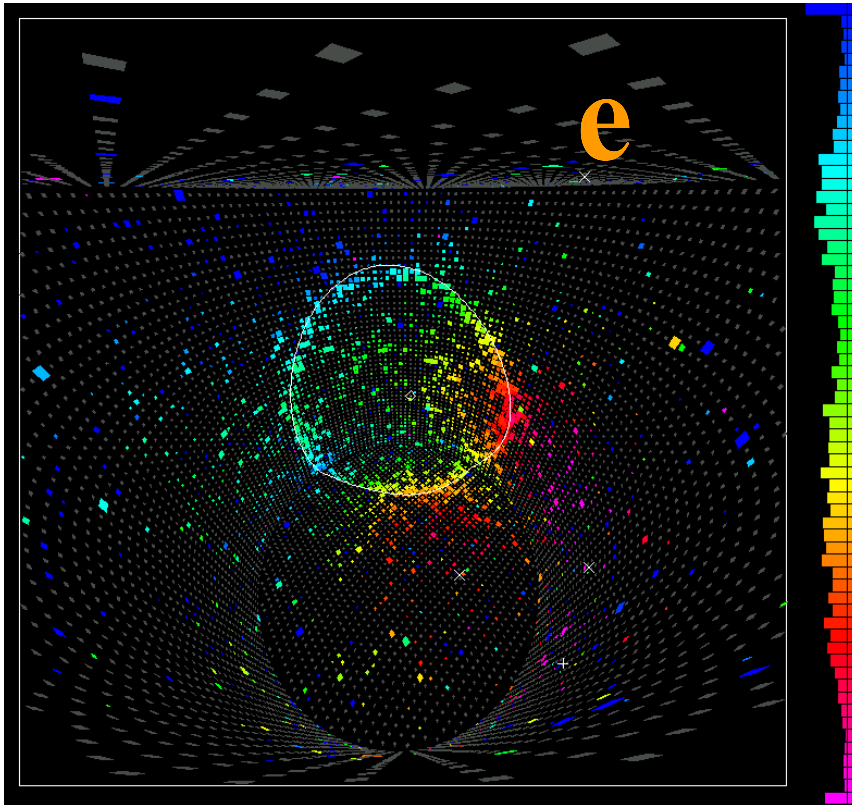
Particle Identification

★ Electrons and muons give slightly different Čerenkov rings !

★ Can therefore tell apart ν_e and ν_μ interactions.



`Clean' ring



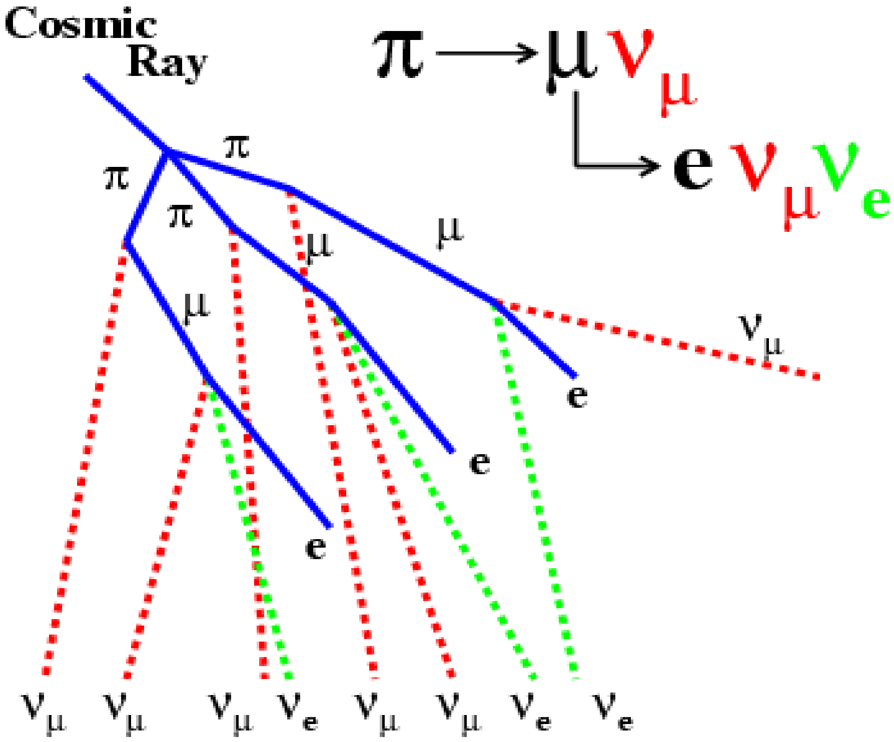
`Diffuse/fuzzy' ring
due to scattering/showering

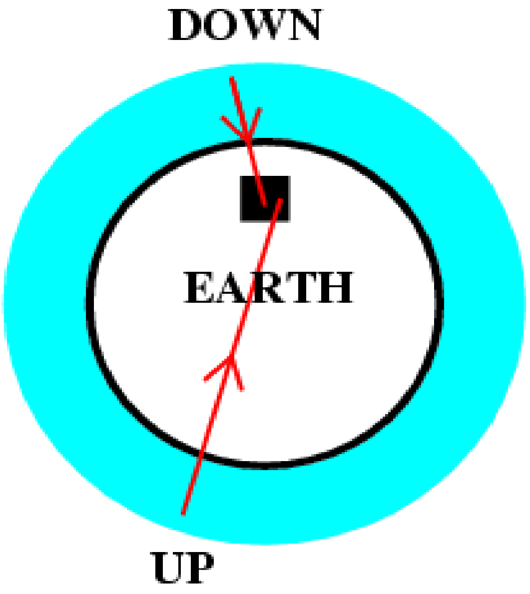
Atmospheric Neutrinos

- ★ **Cosmic Rays (mainly p,He) hitting upper atmosphere produce νs:**

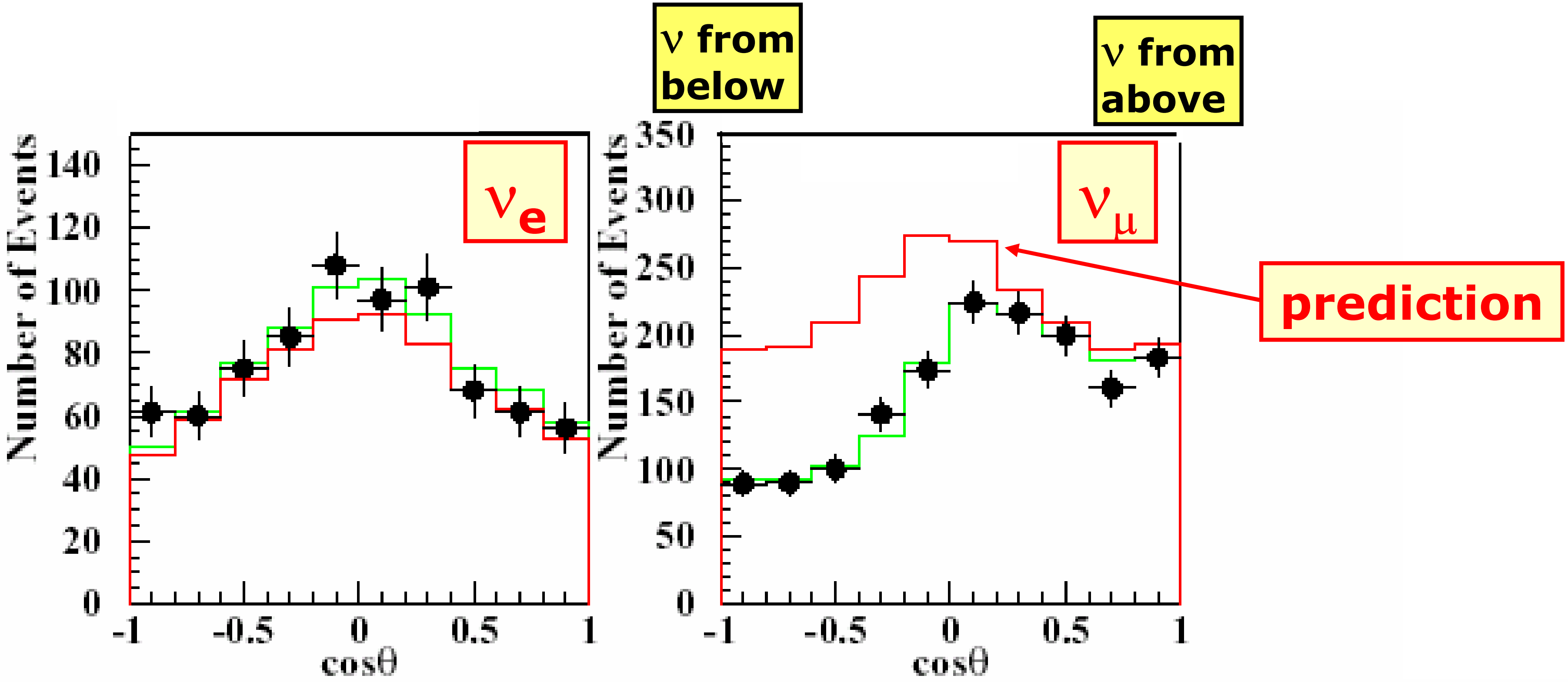
  $\pi \rightarrow \mu\nu_\mu$ **and** $\mu \rightarrow e\nu_e\nu_\mu$ **decays**

- ★ **Expect** $N(\nu_\mu)/N(\nu_e) \sim 2$





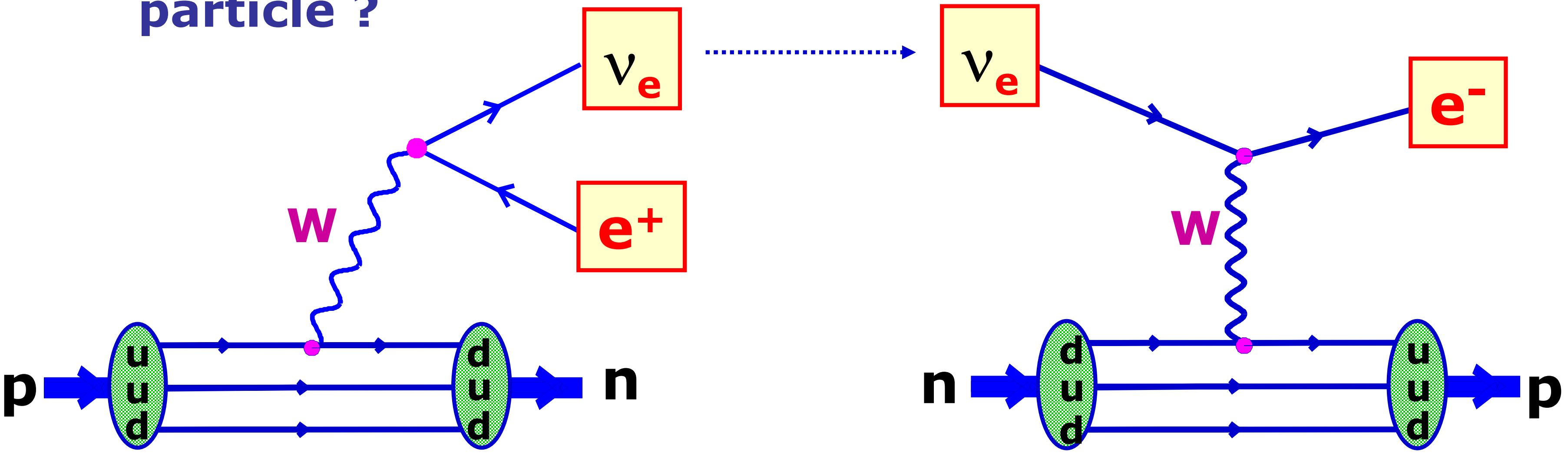
SuperKamiokande Results



- ★ **Electron neutrinos consistent with no oscillations**
- ★ **Deficit of neutrinos coming from below !**
- ★ **ONE OF THE MOST SURPRISING RESULTS OF THE LAST TWENTY YEARS !**

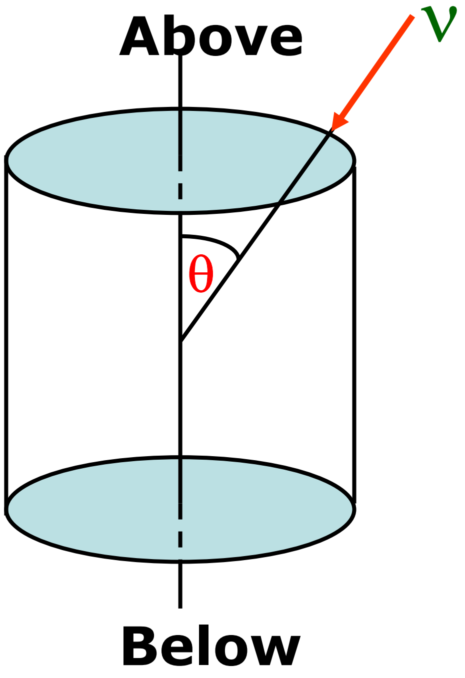
Neutrino Oscillations

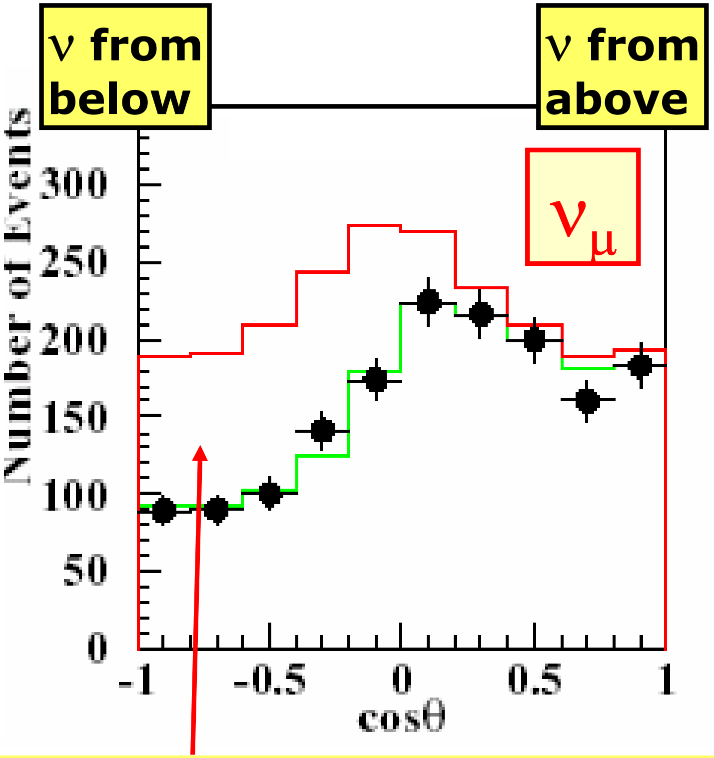
- Now understood as **NEUTRINO OSCILLATIONS**
- **Two major consequences:**
  - ★Neutrinos have mass (albeit extremely small)
  - ★ν_e, ν_μ, ν_τ are not fundamental particles
- Why would you think the ν_e was a fundamental particle ?



- Previously observed that the **neutrino** produced in a process in association with an **electron** always produced an **electron** when it interacted, **never a** μ/τ

★ Therefore, by **definition**, the ν_e is the state which pairs up with an electron in the weak interaction



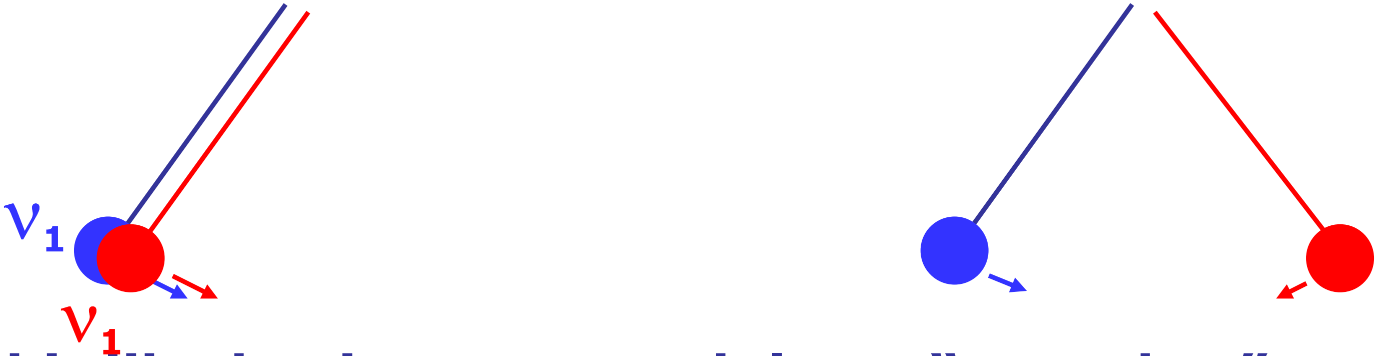


★ Super-Kamiokande observations can be explained if half the ν_μ change into ν_τ once they have travelled more than about **1000 km !**

Neutrino Oscillations

- Suppose ν_μ and ν_τ are not fundamental particles
- Assume they are mixtures of two fundamental neutrino states, ν_1 and ν_2 of mass m_1 and m_2
- These are Quantum Mechanical superpositions
  ~ 50 % probability of being ν_1 and 50 % of ν_2

$$\nu_\mu = \frac{1}{\sqrt{2}}(\nu_1 + \nu_2) \qquad \nu_\tau = \frac{1}{\sqrt{2}}(\nu_1 - \nu_2)$$

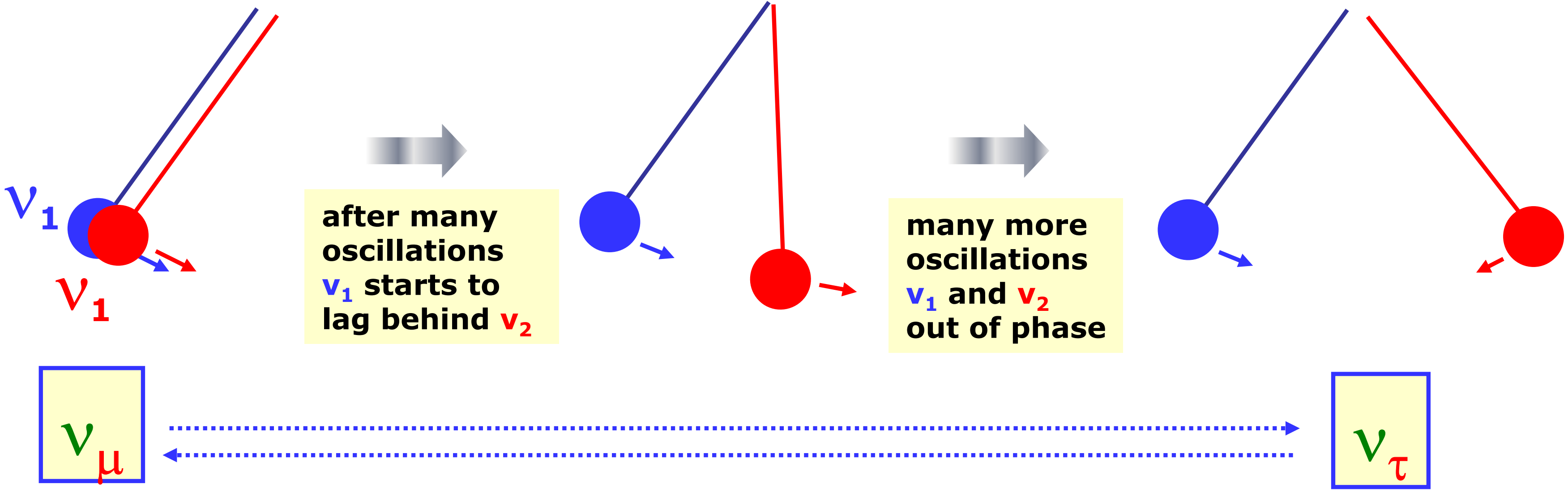


- a bit like having two pendulums "ν_1 and ν_2"
- if they swing in phase its a ν_μ and if it interacts in this state would produce a μ
- if they swing out of phase its a ν_τ and would produce a τ if it were to interact in this state

$$\nu_\mu = \frac{1}{\sqrt{2}}(\nu_1 + \nu_2)$$

$$\nu_\tau = \frac{1}{\sqrt{2}}(\nu_1 - \nu_2)$$

- **suppose we start off with a ν_μ but the masses of ν_1 and ν_2 are slightly different and the pendulums have different oscillation frequencies**



after many oscillations ν_1 starts to lag behind ν_2

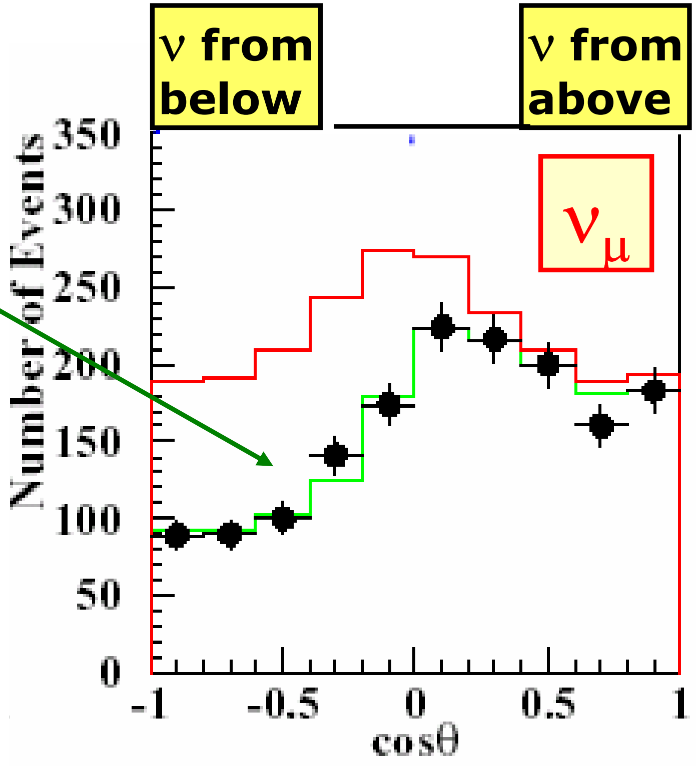
many more oscillations ν_1 and ν_2 out of phase

★Oscillation probability depends on time → depends on distance travelled by the neutrinos, **L** :

$$\text{Prob}(\nu_\mu \to \nu_\tau) \sim \sin^2\left(1.27\frac{L}{E_\nu}[m_3^2 - m_2^2]\right)$$

Explains Super-Kamiokande data if $m_3^2 - m_2^2 = 10^{-20}\ (\mathrm{GeV}/c^2)^2$

Prediction for $\nu_\mu \leftrightarrow \nu_\tau$



NOTE:

- ★Only gives measure of difference in squares of neutrino masses
- ★**BUT** oscillations require a non-zero mass difference i.e. neutrinos have a small mass

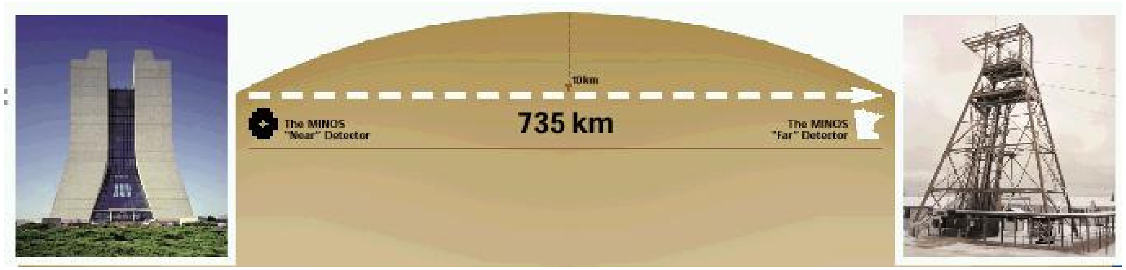
The MINOS Experiment

Until recently all neutrino oscillation experiments used naturally occurring neutrinos (atmosphere, solar)

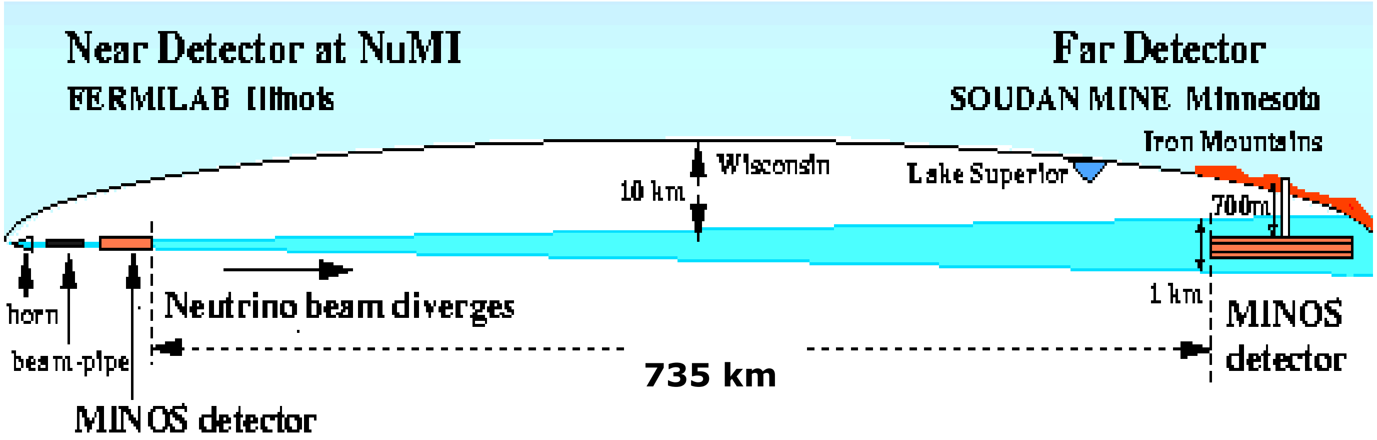
Physicist naturally like to be in control !

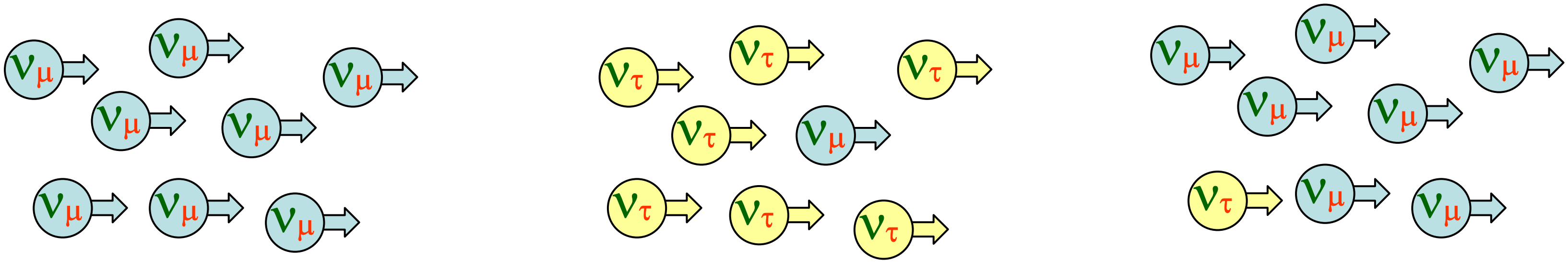
So we constructed our own neutrino beam….

MINOS



MINOS : Basic Idea

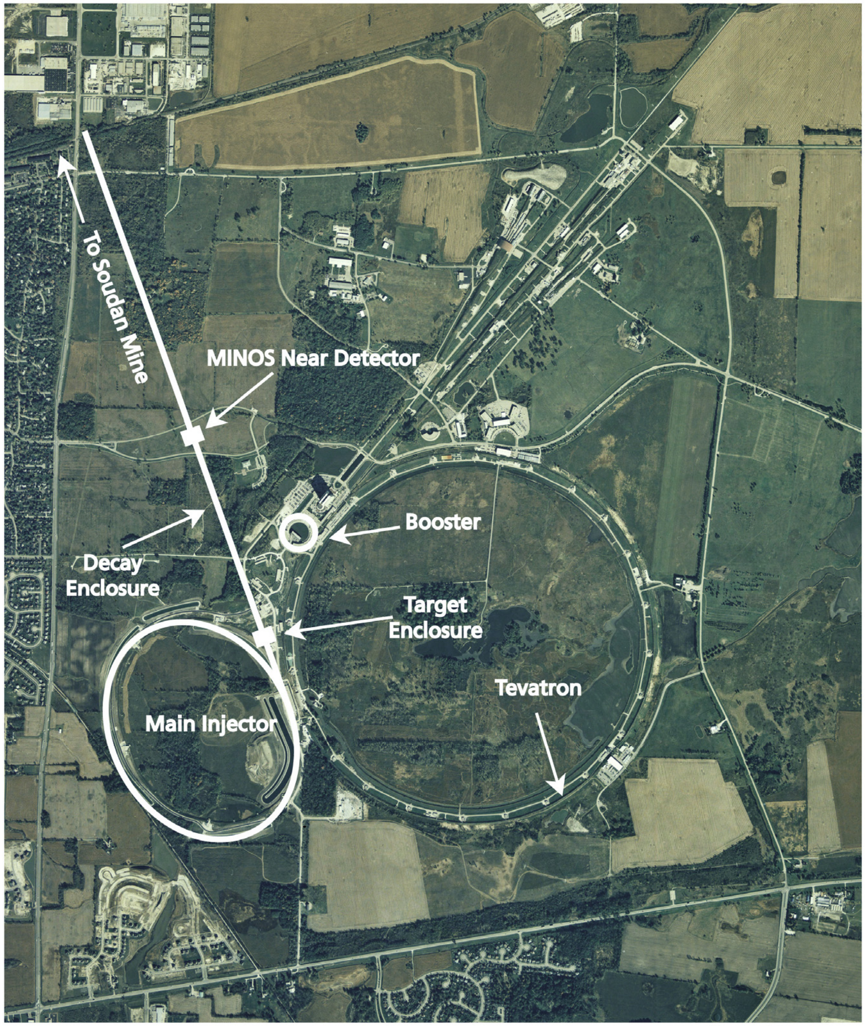




Two detectors !

- ★ **Near : 1km away (sees a pure ν_μ beam)**
- ★ **Far : 735km away (sees oscillated beam $\nu_\mu + \nu_\tau$)**

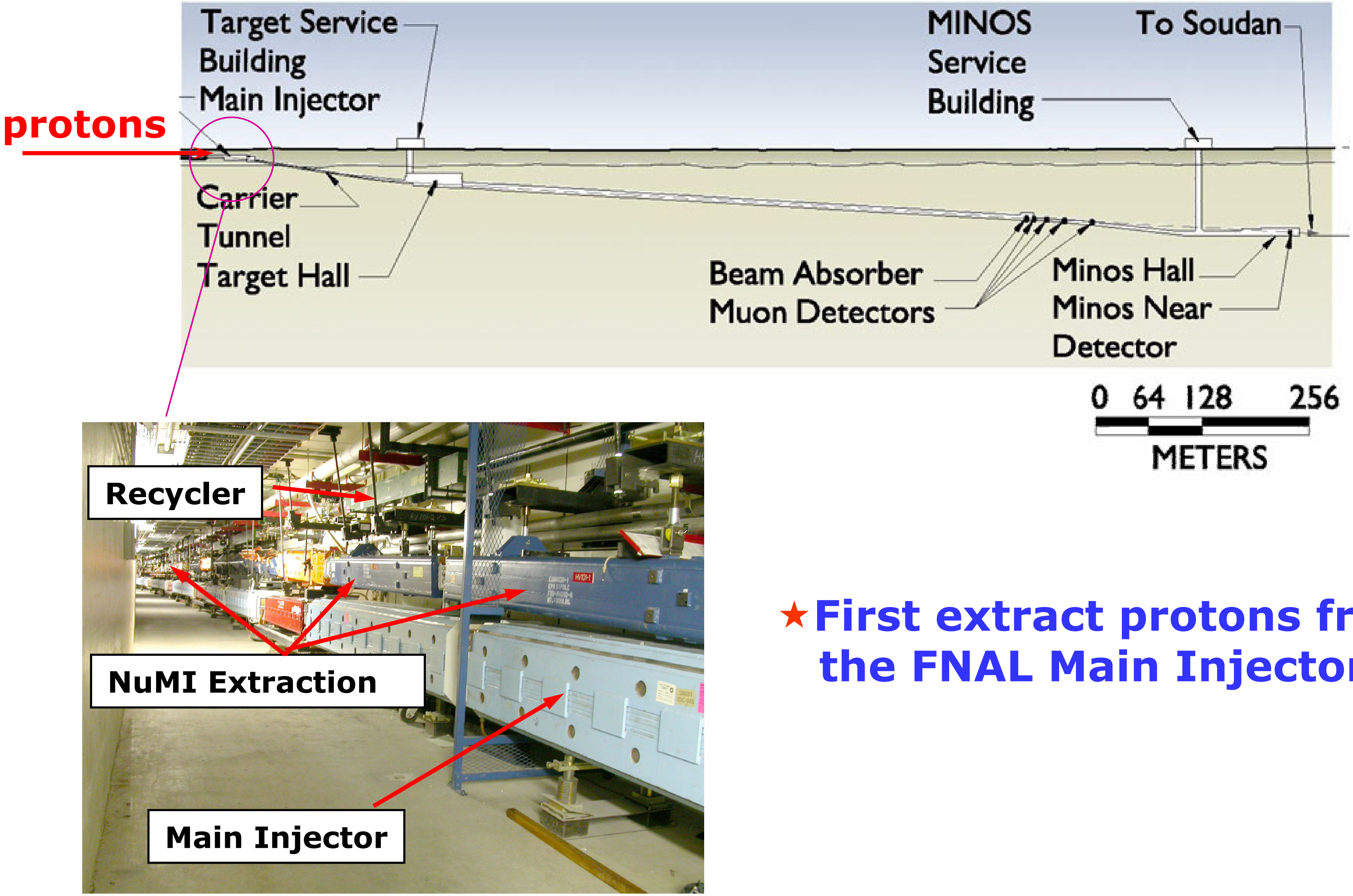
Making a Neutrino Beam



FERMILAB #98-765D

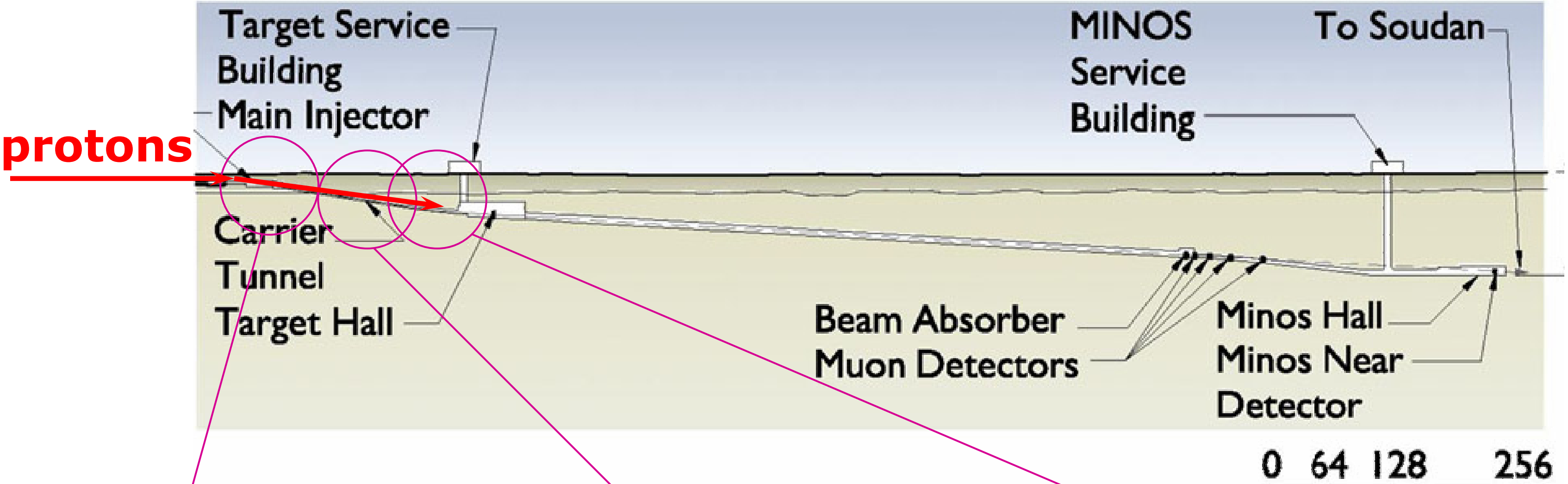
- ★ Need a collimated ν beam
- ★ BUT can't focus neutrinos
- ★ Therefore focus particles which decay to neutrinos
  e.g. pions, kaons
- ★ Easy to make pions !
- ★ Start with 120 GeV protons
- ★ Smash into graphite target
- ★ Intense beam : 0.3 MW on target

The NuMI ν beam : I



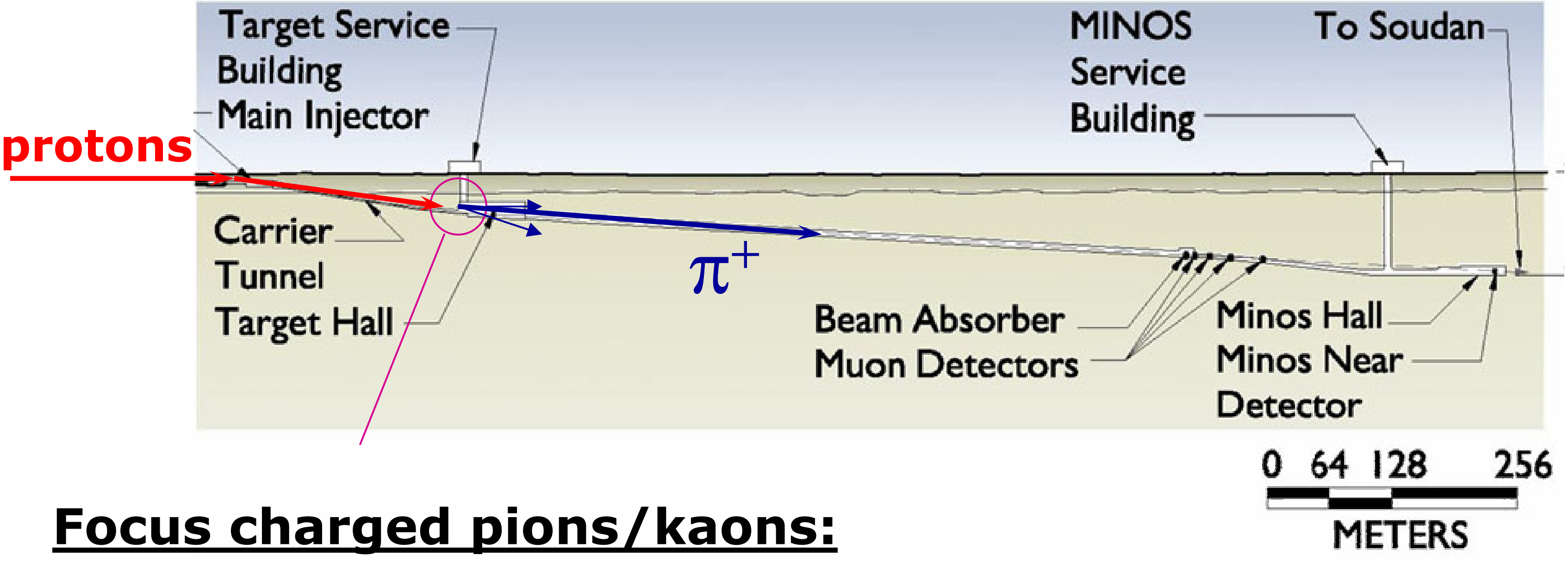
★ **First extract protons from the FNAL Main Injector**

The NuMI ν beam : II



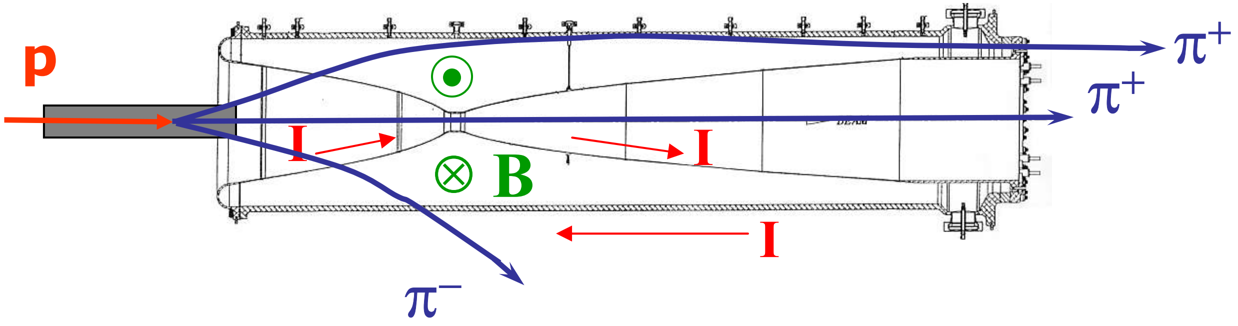
- ★ **Transport beam underground into solid bedrock (for civil construction reasons)**
- ★ **Beam points 3.3° downwards**

The NuMI ν beam : III

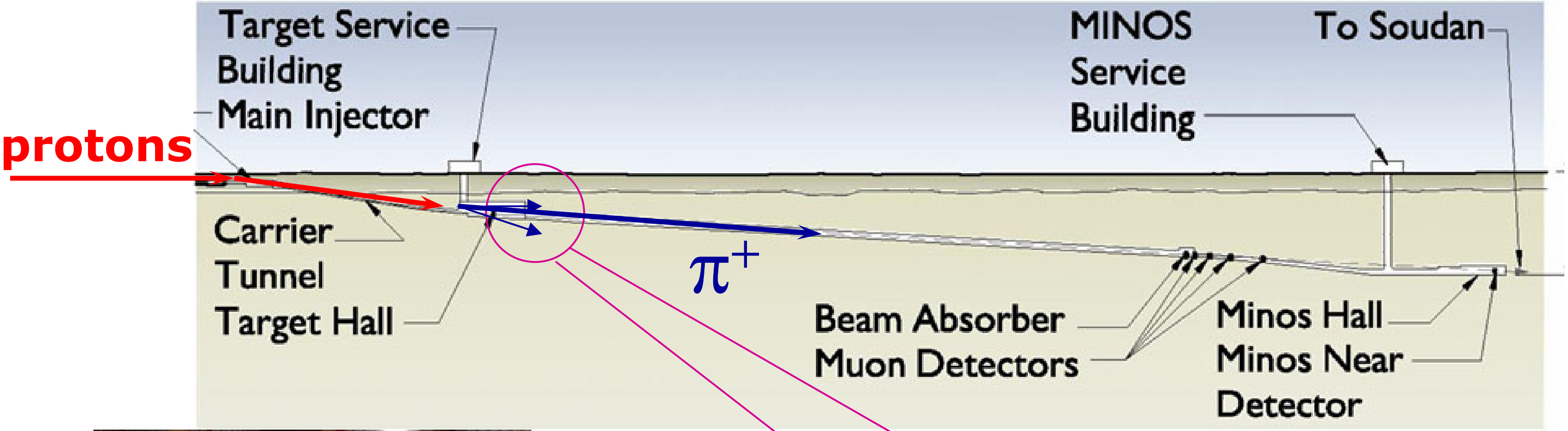


Focus charged pions/kaons:

- **Horn pulsed with 200 kA**
- **Toroidal Magnetic field *B* ~ I/*r* between inner and outer conducters**



The NuMI ν beam : IV

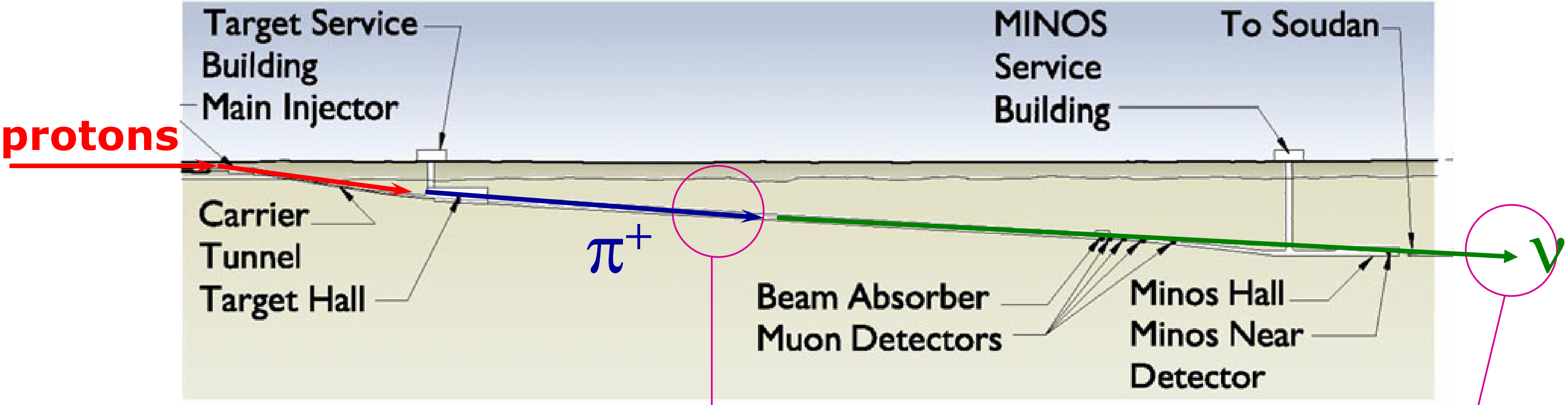



Horn on mounting


Before shielding


Shielding Installation

The NuMI ν beam : V

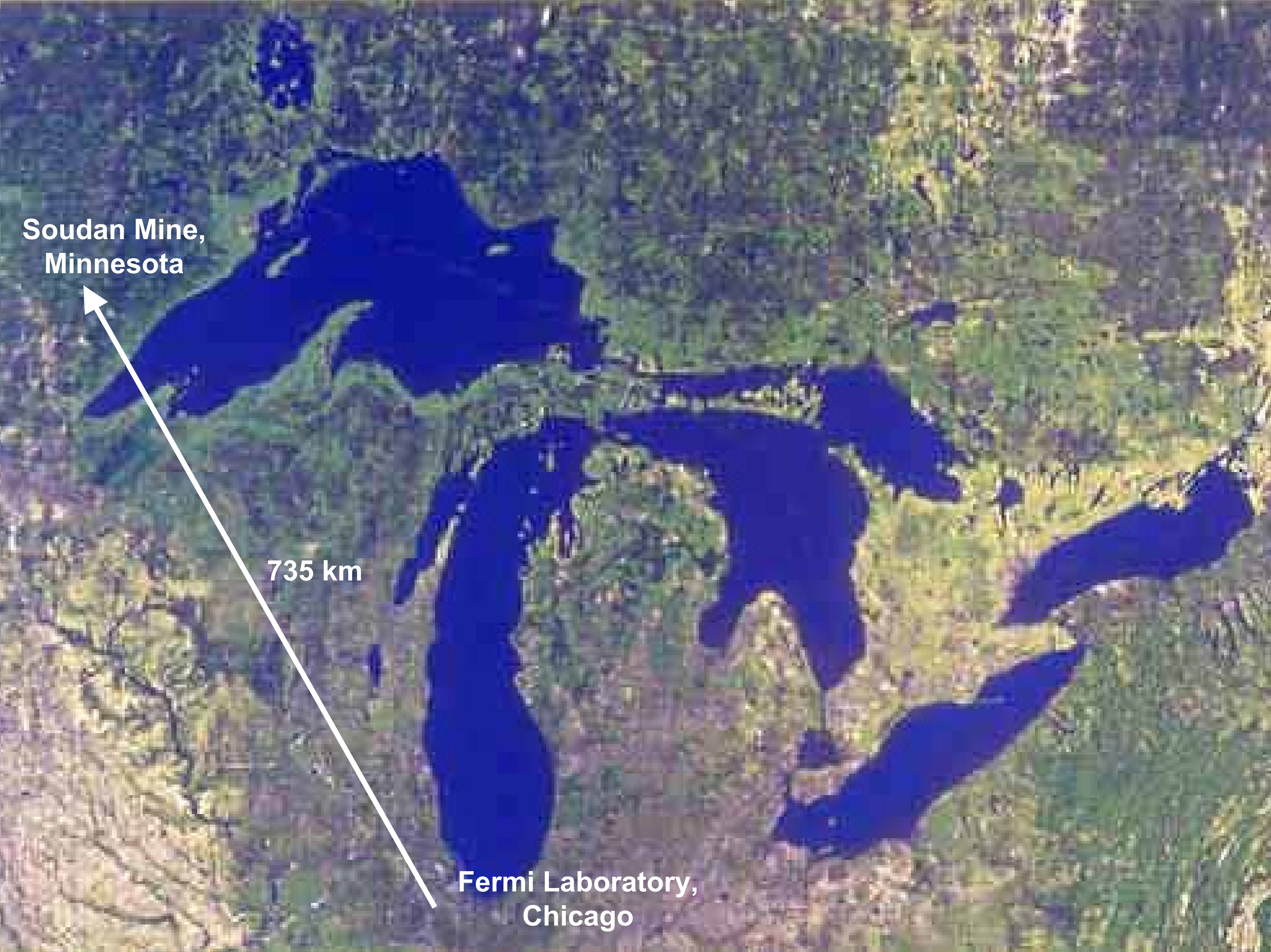


675 m long decay pipe

- ★ Need long decay pipe to allow all the pions to decay:

  $$\pi^+ \rightarrow \mu^+ \nu_\mu$$

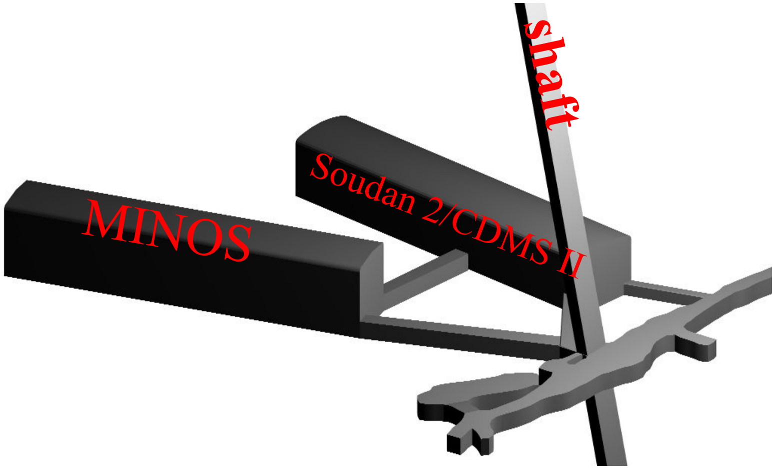
- ★ Now draw the Feynman diagram !
  (hint a π^+ is $u\bar{d}$ meson)



Going underground

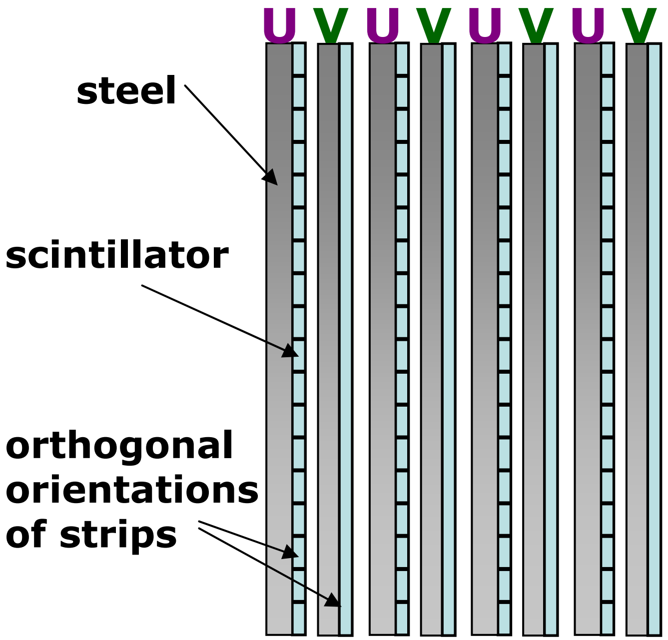
- **MINOS Far Detector located deep underground**
  - **shield from cosmic-rays**

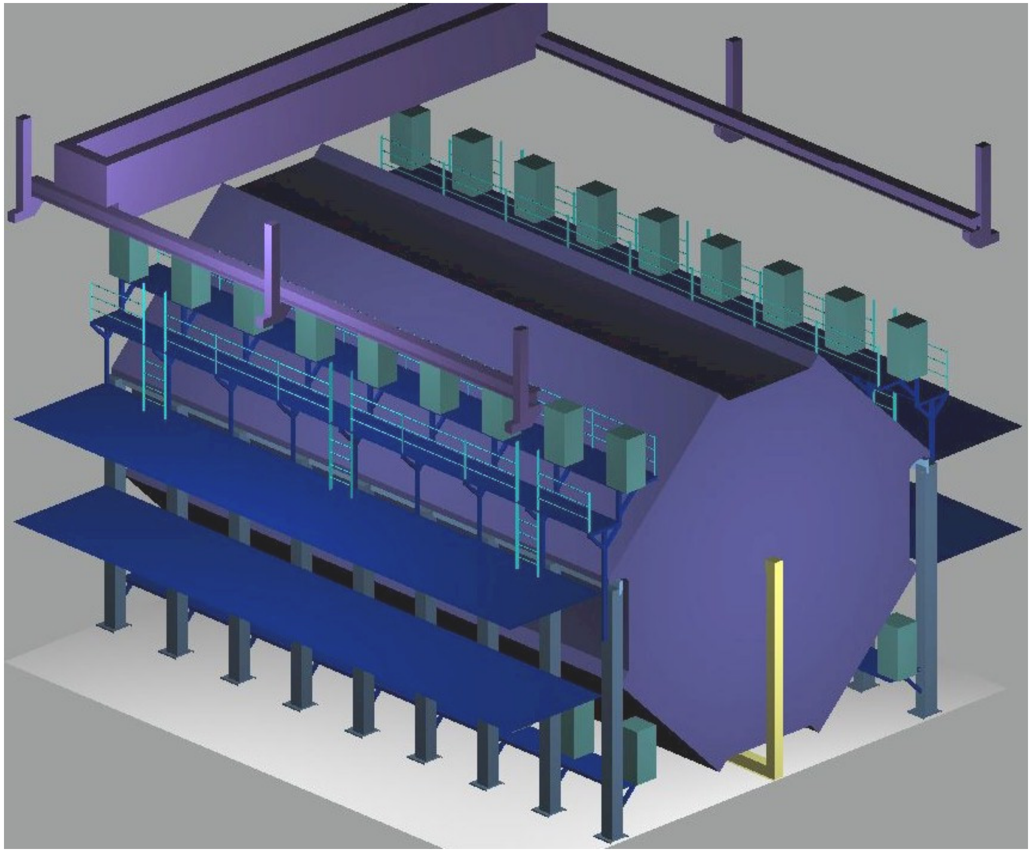
Photo by Jerry Meier

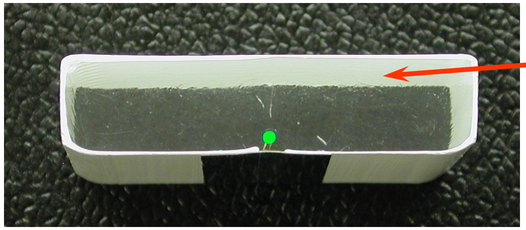


MINOS Far Detector

- 8m octagonal steel & scintillator “tracking calorimeter”
- Magnetized Iron (B~1.5T)
- 484 planes of scintillator



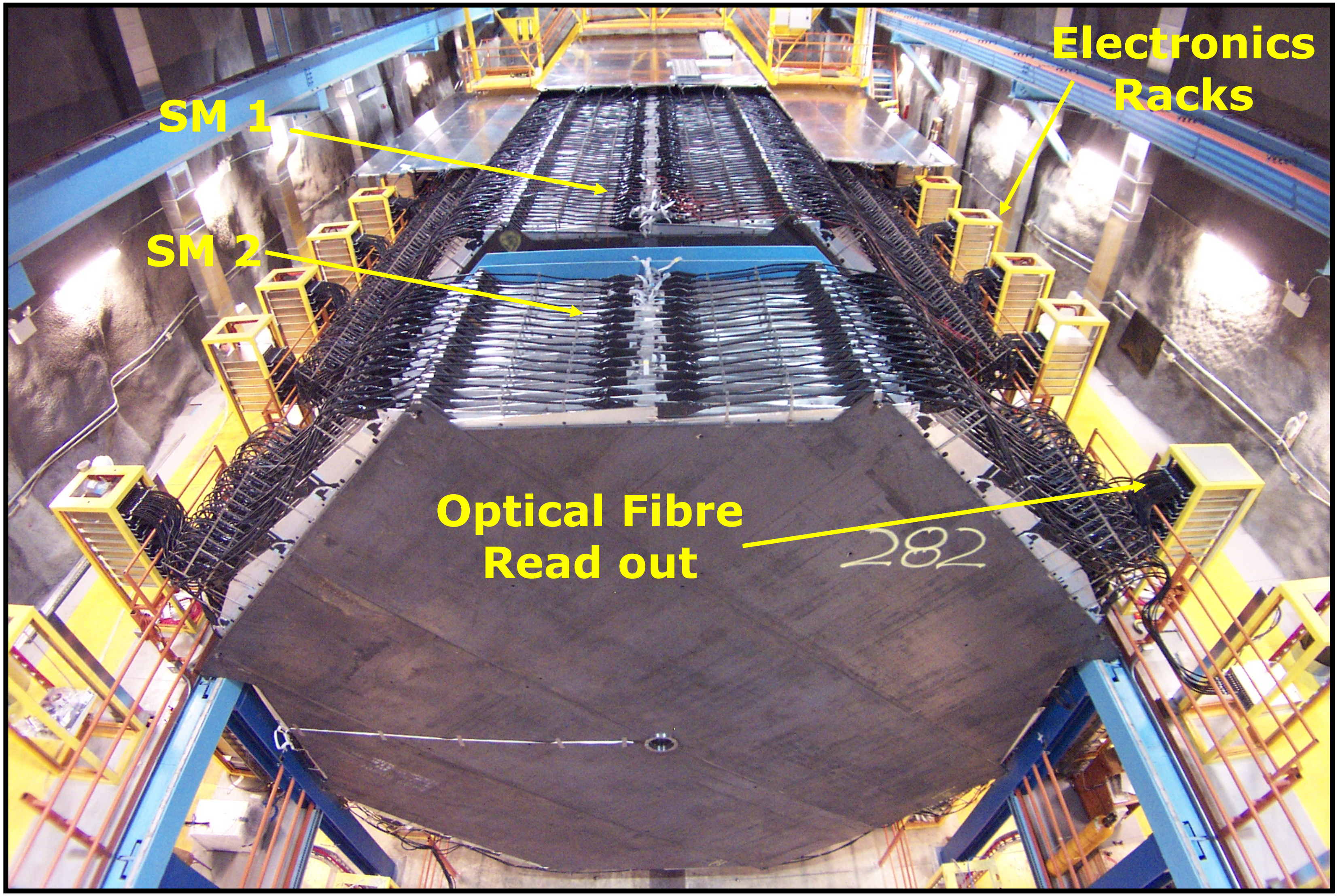




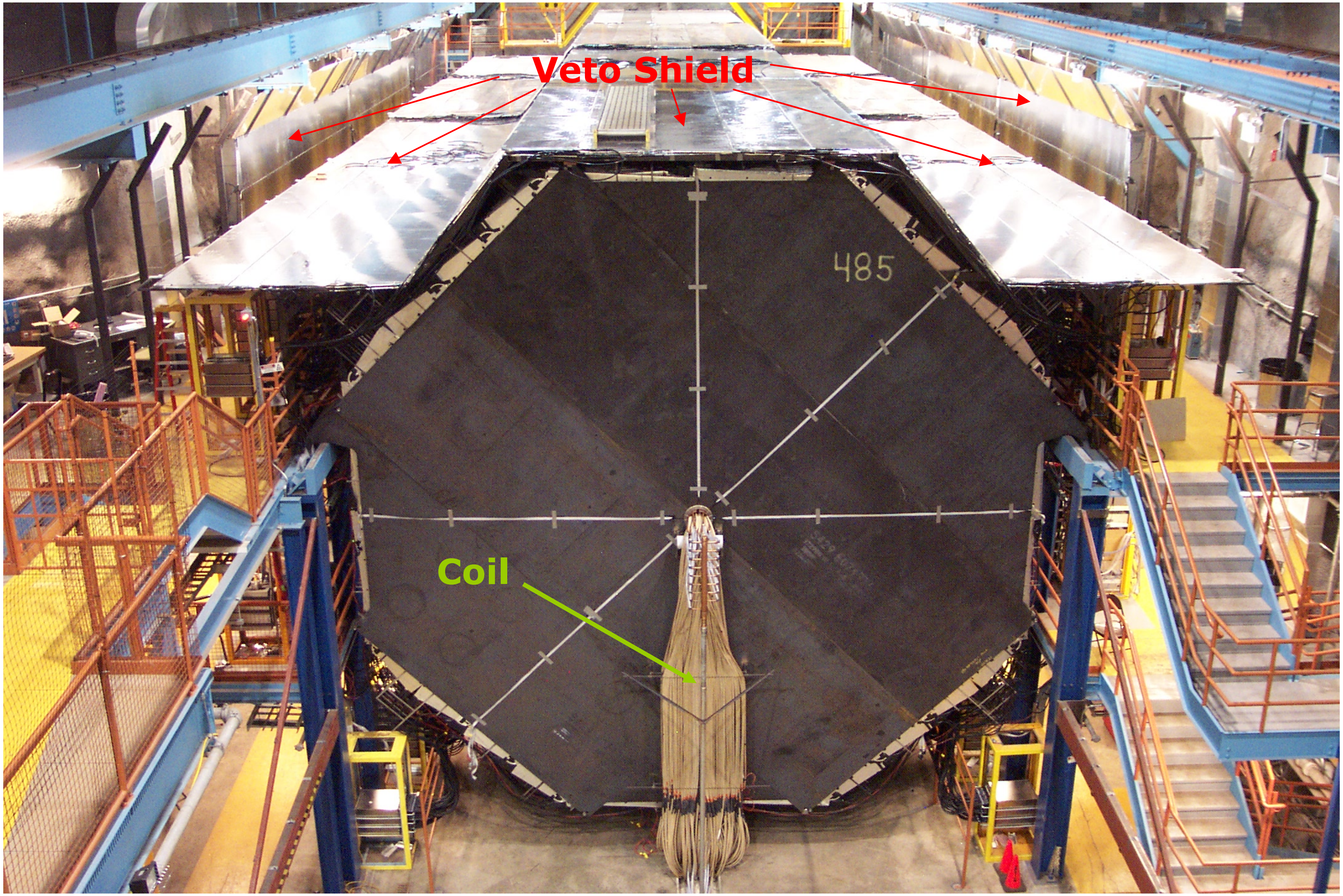
✦Scintillation light collected by **WLS** fibre glued into groove

✦Readout by multi-pixel PMTs

MINOS FarDet during installation

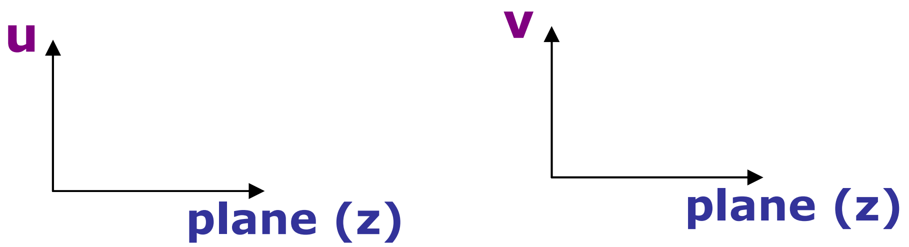


Far Detector fully operational since July 2003



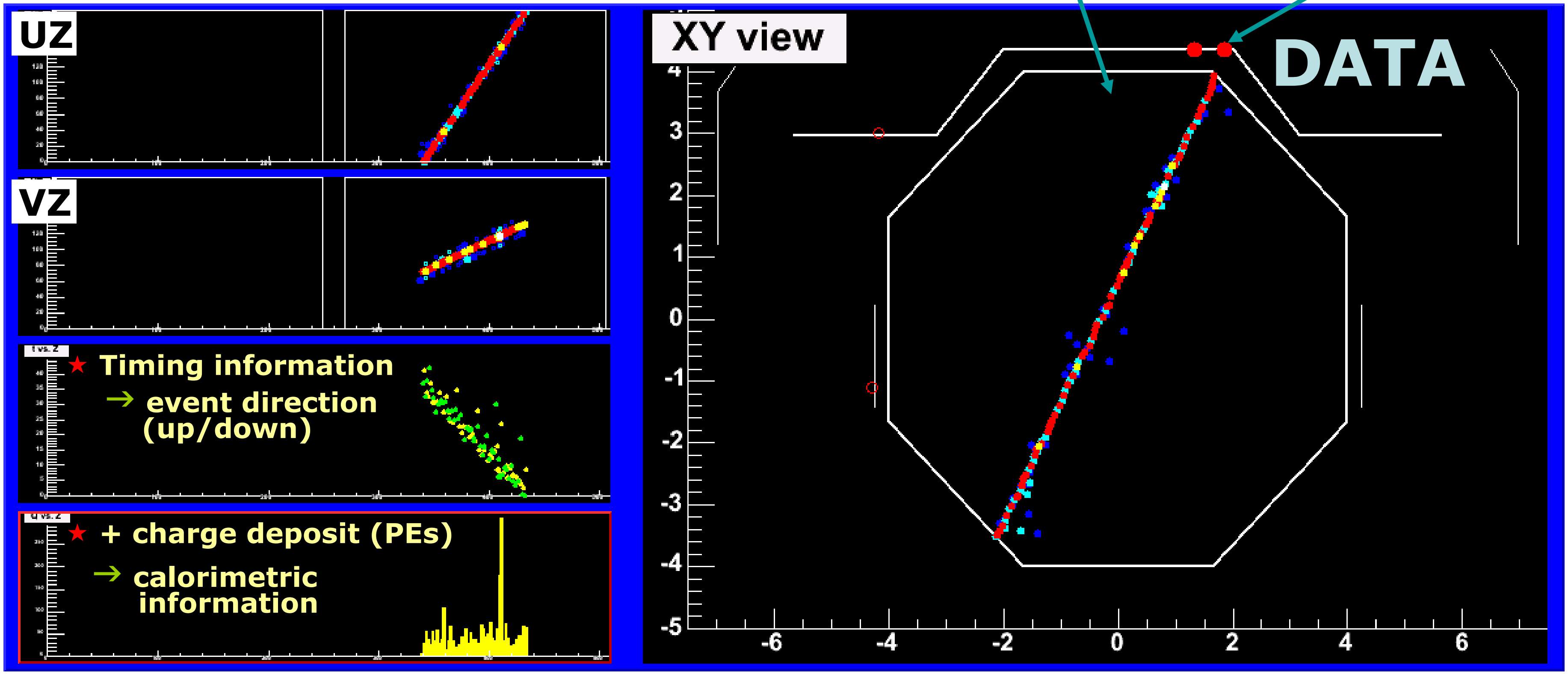
Event Information

- ★ **Two 2D views of event**



- ★ **Software combination to get `3D' event**

Veto shield hit

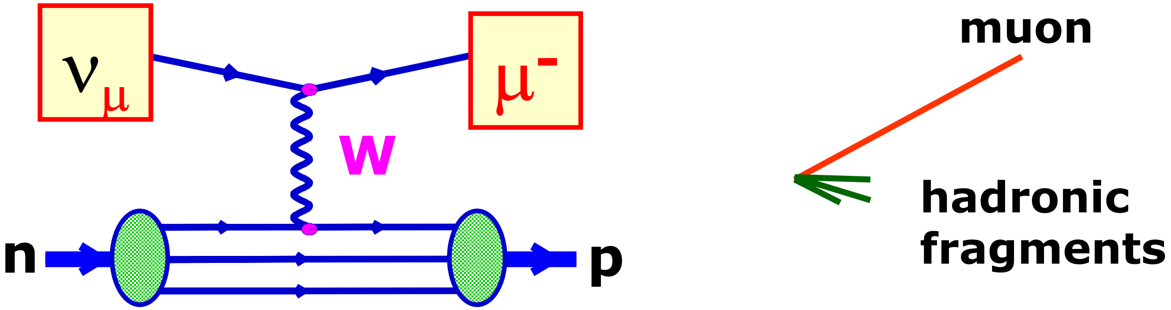


★ Timing information
→ event direction (up/down)

★ + charge deposit (PEs)
→ calorimetric information

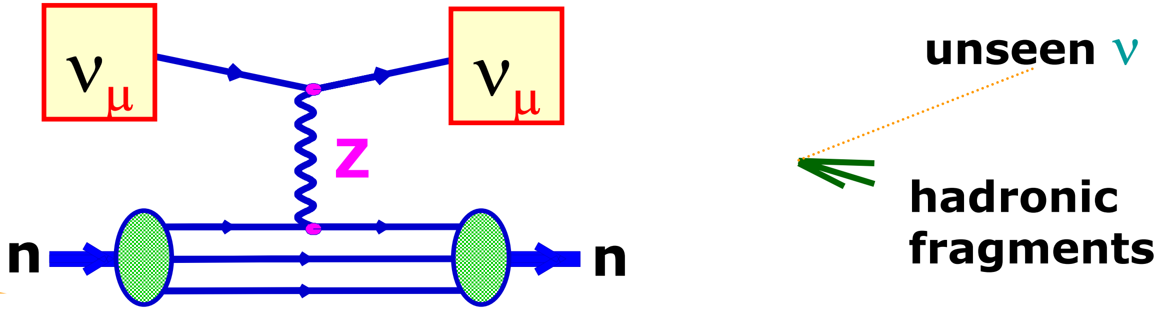
Neutrino interactions in MINOS

ν_μ Charged Current (CC)



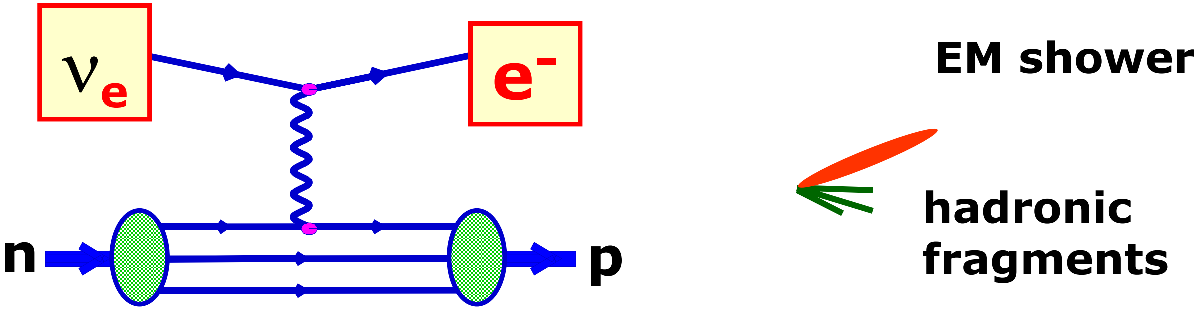
Neutral Current (NC)

"Background"



ν_e CC

(if $\nu_\mu \leftrightarrow \nu_e$)

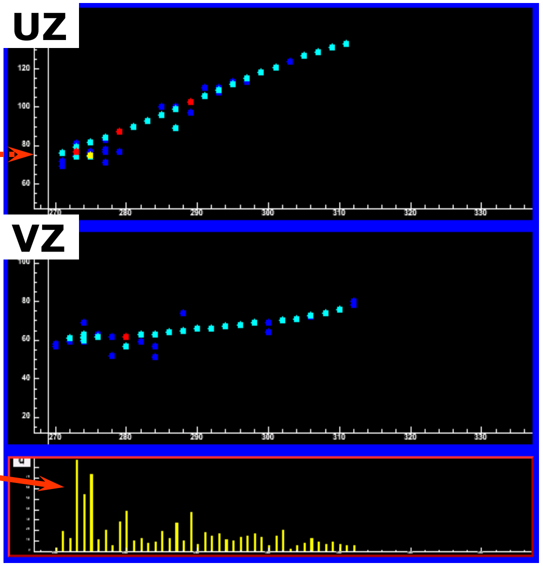


MINOS Beam Physics (Simulation)

ν_μ CC Event

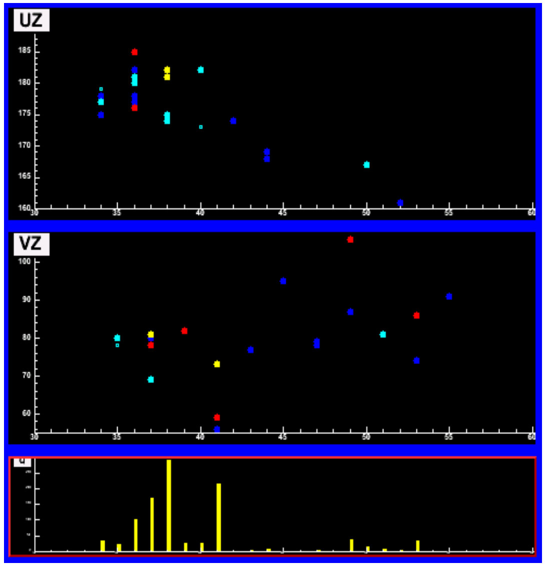
ν

- μ track
- +hadronic activity



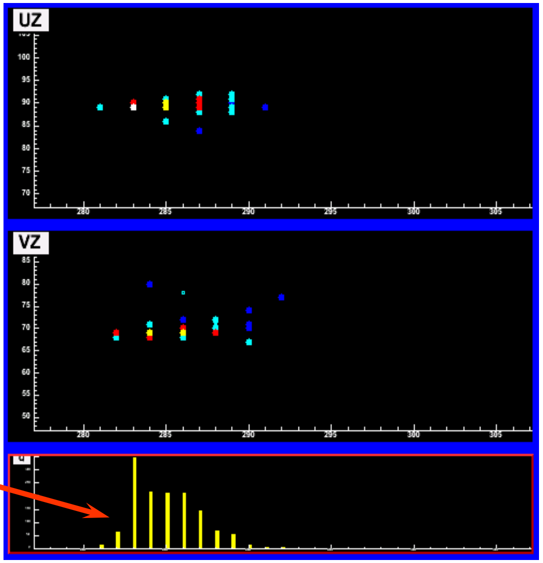
NC Event

- often diffuse



ν_e CC Event

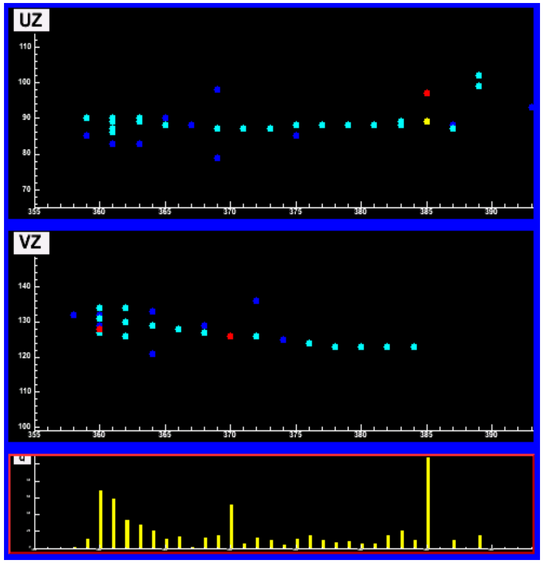
- compact shower
- typical EM shower profile



NC Event

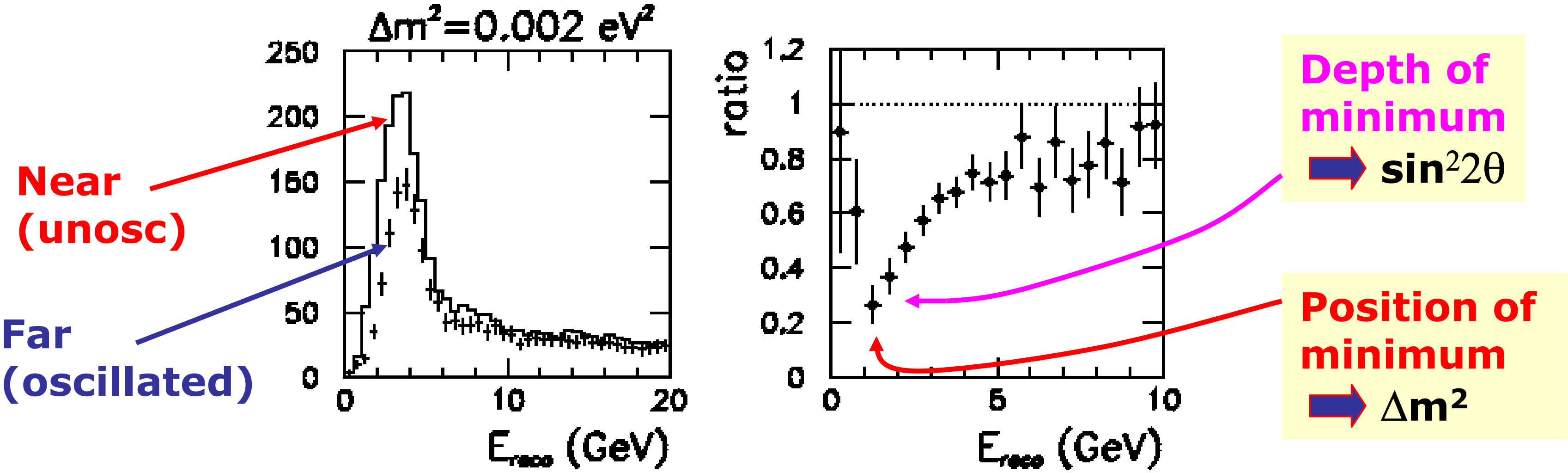
- can mimic

  ν_μ , ν_e



Energy Reconstruction

Recall: trying to measure oscillation probability as as function of neutrino energy



Near (unosc)

Far (oscillated)

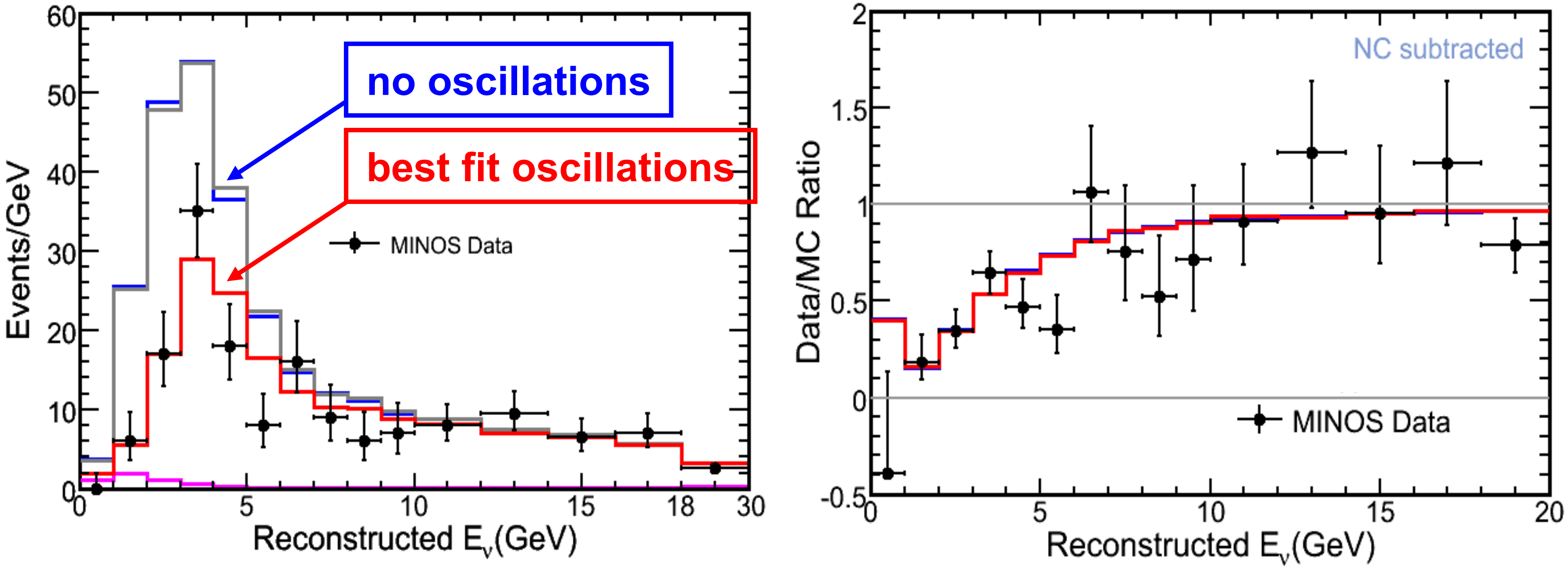
Depth of minimum ➡ $\sin^2 2\theta$

Position of minimum ➡ Δm^2

$$P(\nu_\mu \to \nu_\tau) \approx \sin^2 2\theta_{23} \sin^2\left(\frac{1.27 L \Delta m^2_{23}}{E}\right)$$

MINOS First Results

- First results (Summer 2006) – relatively small amount of data



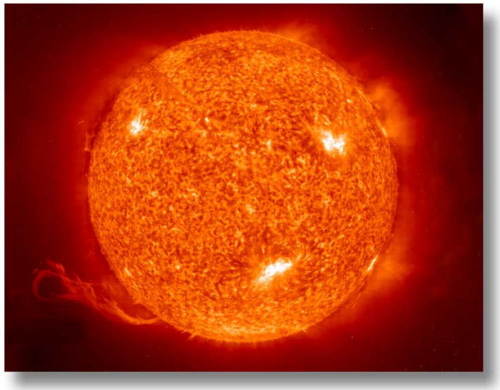
no oscillations

best fit oscillations

$$|\Delta m^2_{32}| = 2.38 \pm 0.18 \times 10^{-3}\,\mathrm{eV}^2$$

★**Already better than 10 % precision !**

What do we know about Neutrino Masses?



★Also see neutrino oscillations of ν_e from the sun

Solar Neutrinos : $m_2^2 - m_1^2 = 10^{-22}\ (\mathrm{GeV}/c^2)^2$

Atmospheric Neutrinos : $m_3^2 - m_2^2 = 10^{-20}\ (\mathrm{GeV}/c^2)^2$

★ Neutrino oscillations only sensitive to differences in mass - don't give a measure of the mass

★ If we assume $m_3 > m_2 > m_1$ then suggests:

$m_3 = 10^{-11}\ \mathrm{GeV}/c^2$ 1/100000000000 m_τ

$m_2 = 10^{-13}\ \mathrm{GeV}/c^2$ 1/100000000000 m_μ

Not understood why neutrino masses so very small !

Summary

- ★ **Just recently starting to understand nature of NEUTRINOS**
- ★ **WEAK interaction due to exchange of massive W bosons (~ 80 x mass of proton)**

Next handout will discuss the unification of the WEAK and Electromagnetic forces