Neutrino Physics

THE UNIVERSITY OF
WARWICK

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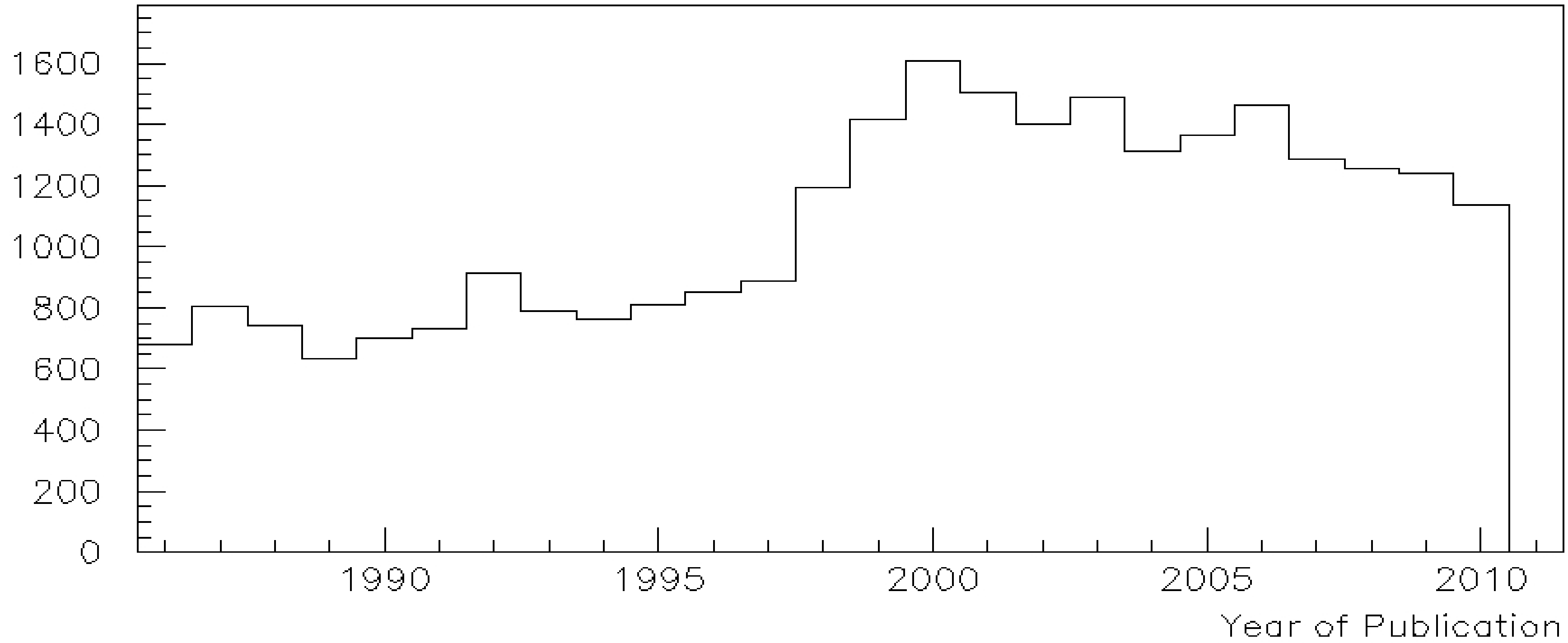
Course Map

1. History of the neutrino, detection, neutrino interactions
2. Neutrino mass, direct mass measurements, double beta decay, flavour oscillations
3. Unravelling neutrino oscillations experimentally
4. Where we are and where we're going

References

- K. Zuber, “Neutrino Physics”, IoP Publishing 2004
- C. Giunti and C.W.Kim, “Fundamentals of Neutrino Physics and Astrophysics”, Oxford University Press, 2007.
- R. N. Mohaptara and P. B. Pal, “Massive Neutrinos in Physics and Astrophysics”, World Scientific (2nd Edition), 1998
- H.V. Klapdor-Kleingrothaus & K. Zuber, “Particle Astrophysics”,IoP Publishing, 1997.
- Two Scientific American articles:
  - “Detecting Massive Neutrinos”, E. Kearns, T. Kajita, Y. Totsuka, Scientific American, August 1999.
  - “Solving the Solar Neutrino Problem”, A.B. McDonald, J.R. Klein, D.L. Wark, Scientific American, April 2003.
- Plus other Handouts

Caveat



Neutrino physics is a diverse field - I can't possibly cover it all in one series of lectures

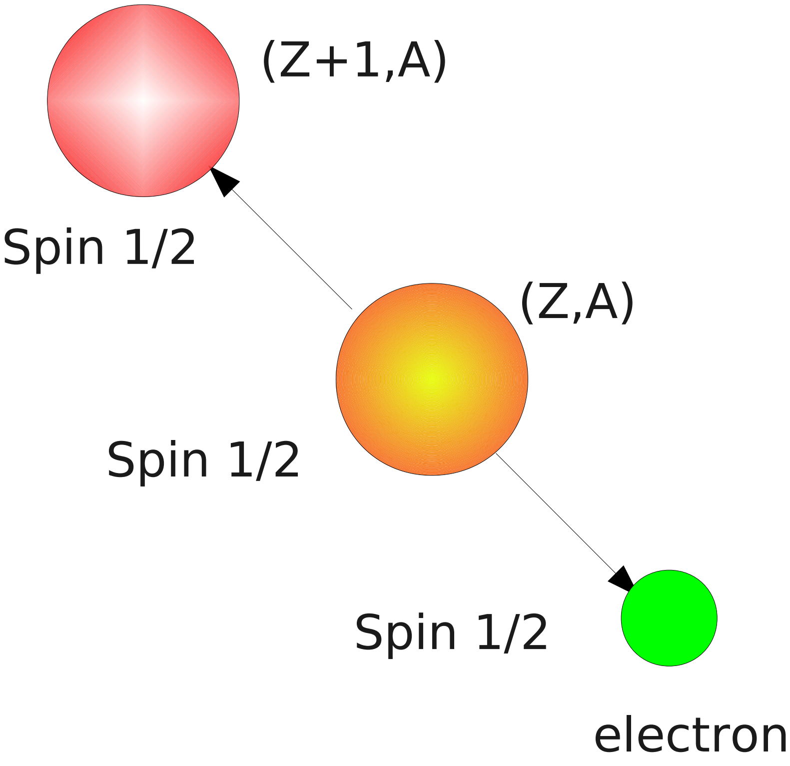
I will blatantly cover that area in which I can reasonably be called an expert – neutrino masses and accelerator based mass measurements.

Lecture 1

In which history is unravelled, desperation
is answered, and the art of neutrino generation and
detection explained

Crisis

It is 1914 – the new study of atomic physics is in trouble



(Z+1,A)

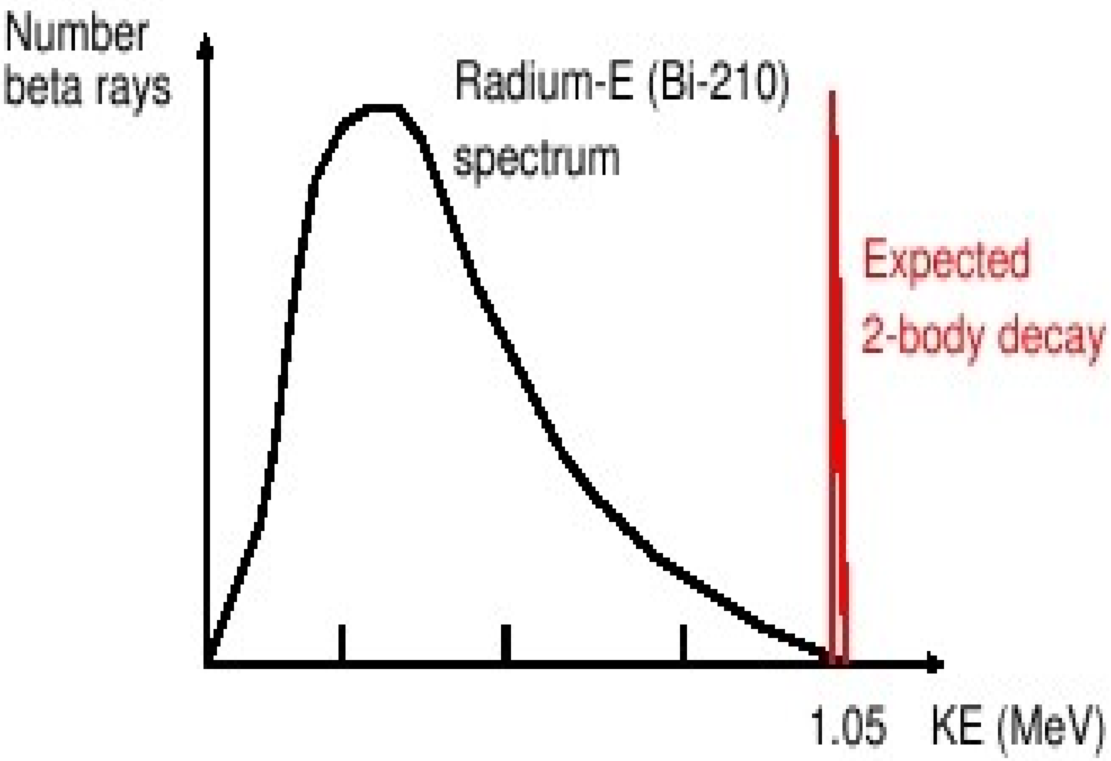
Spin 1/2

(Z,A)

Spin 1/2

Spin 1/2

electron



Spin ½ ≠ spin ½ + spin ½

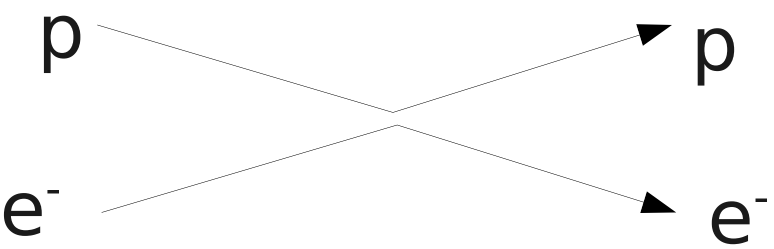
$E_{Ra} \neq E_{Bi} + e$

“At the present stage of atomic theory we have no arguments for upholding the concept of energy balance in the case of β-ray disintegrations.”

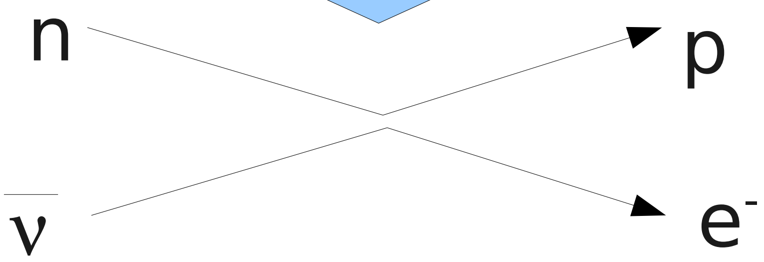
“Desperate remedy.....”
“I do not dare publish this idea....”
“I admit my way out may look improbable....”
“Weigh it and pass sentence....”

“You tell them. I'm off to a party”

Fermi Theory (1926)

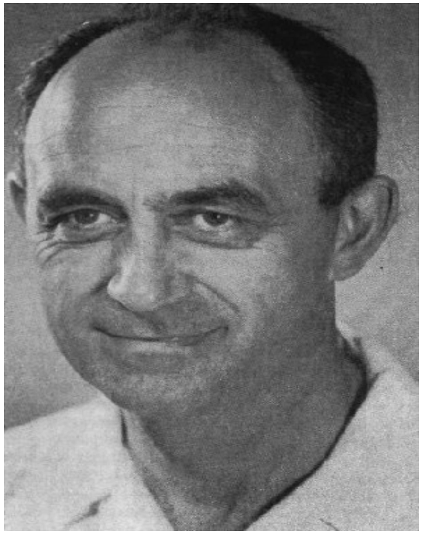


$$L = e^2[\bar{\phi}_p(x)\gamma^\mu\phi_p(x)][\bar{\phi}_e(x)\gamma_\mu\phi_e(x)]$$



$$L = G_F[\bar{\phi}_p(x)\gamma^\mu\phi_n(x)][\bar{\phi}_e(x)\gamma_\mu\phi_\nu(x)]$$

NB Vector-Vector



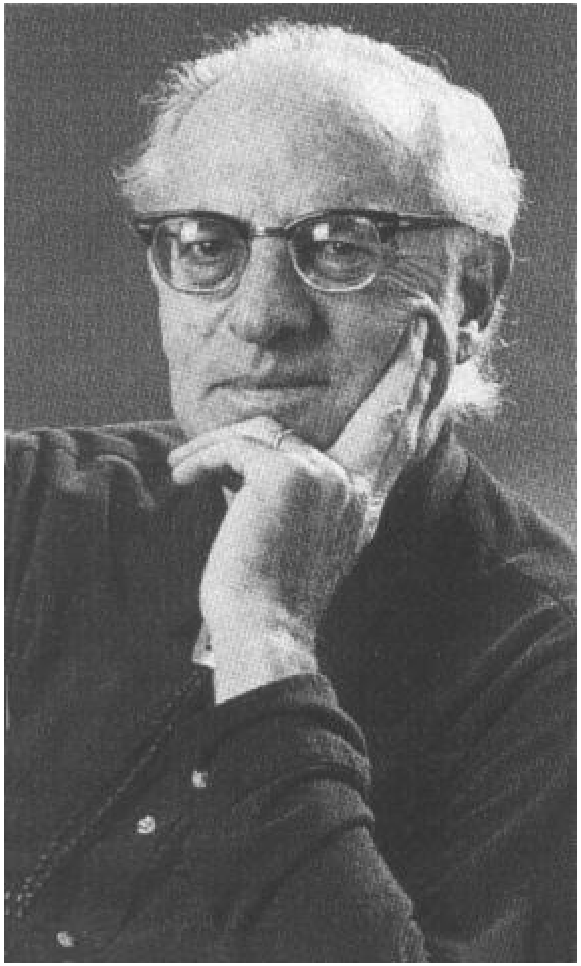
Enrico Fermi

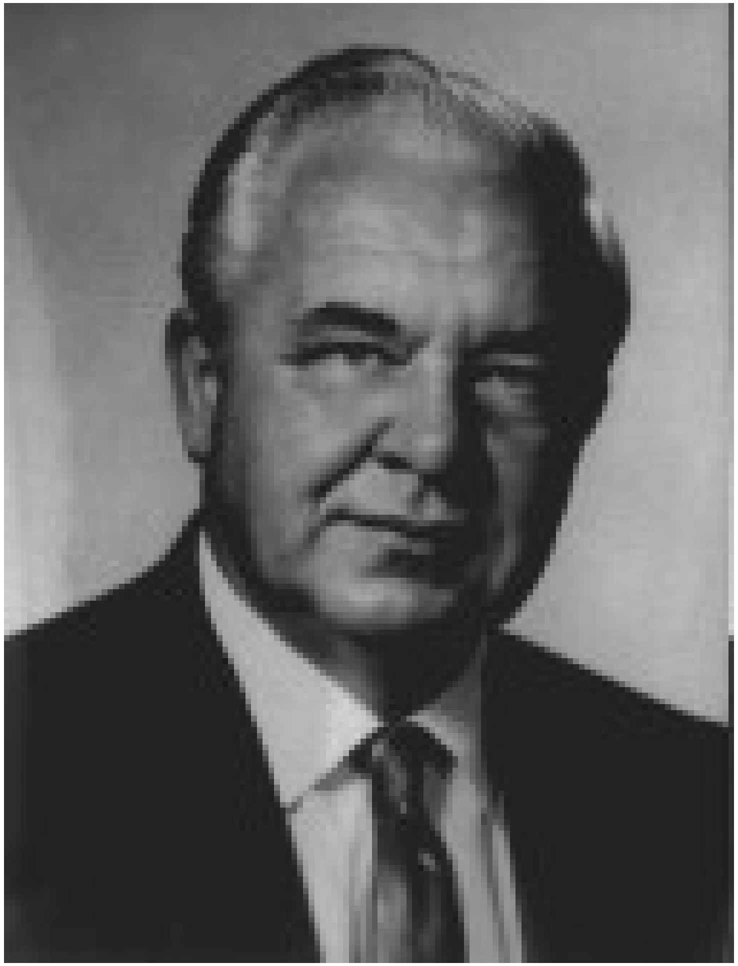
$\sigma \sim 10^{-44}$ cm^2 for 2 MeV ν

$\lambda_{lead} \approx$ 22 light years

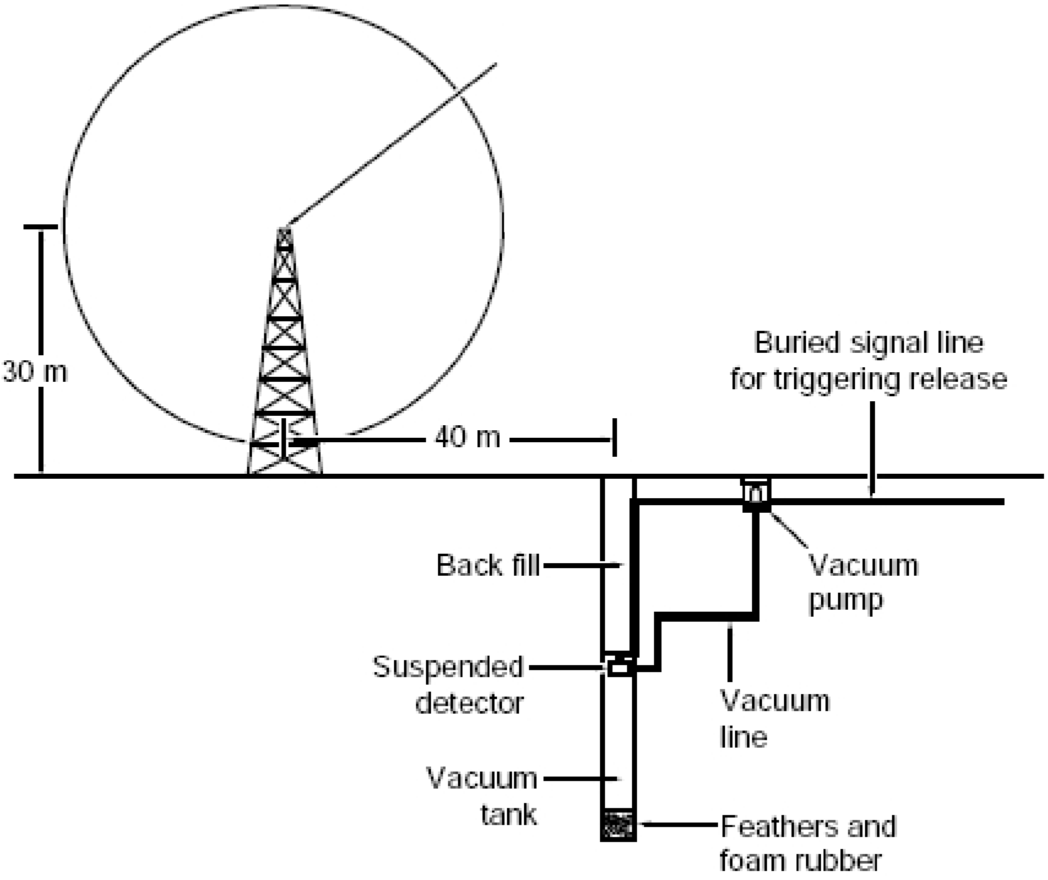
Detection of the Neutrino

1950 – Reines and Cowan set out to detect ν





Project Poltergeist - 1951



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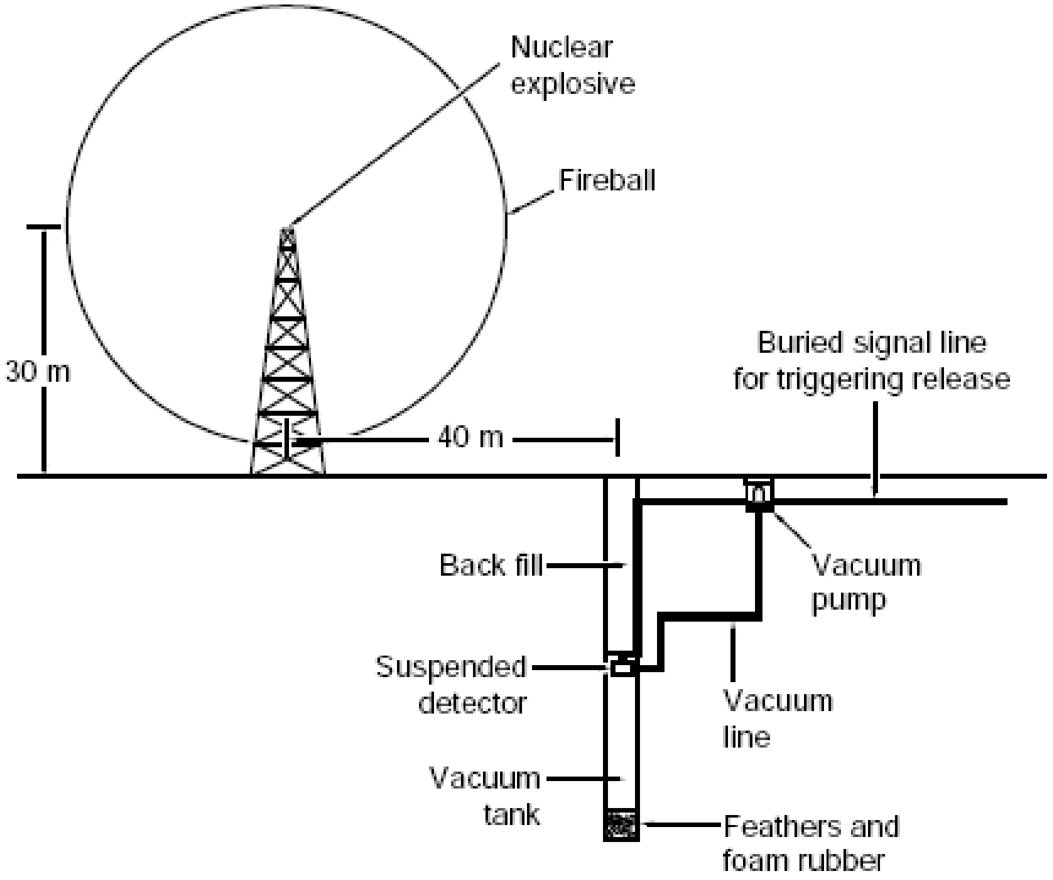


I. Explode bomb
II. At same time let detector fall in vacuum tank
III. Detect neutrinos
IV. Collect Nobel prize

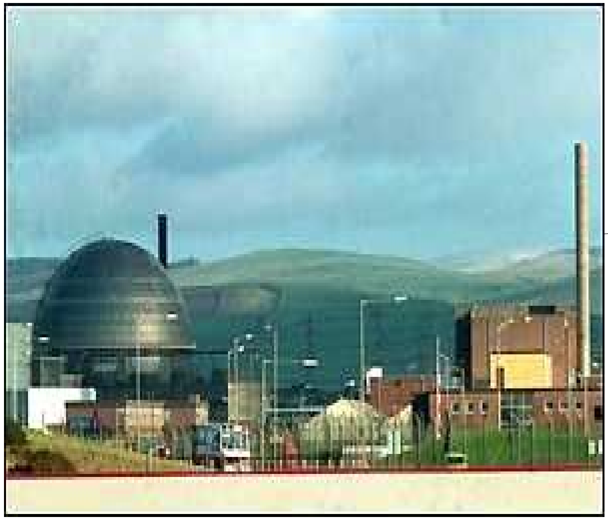
OK – but repeatability is a bit of a problem

Idea Number 2 - 1956

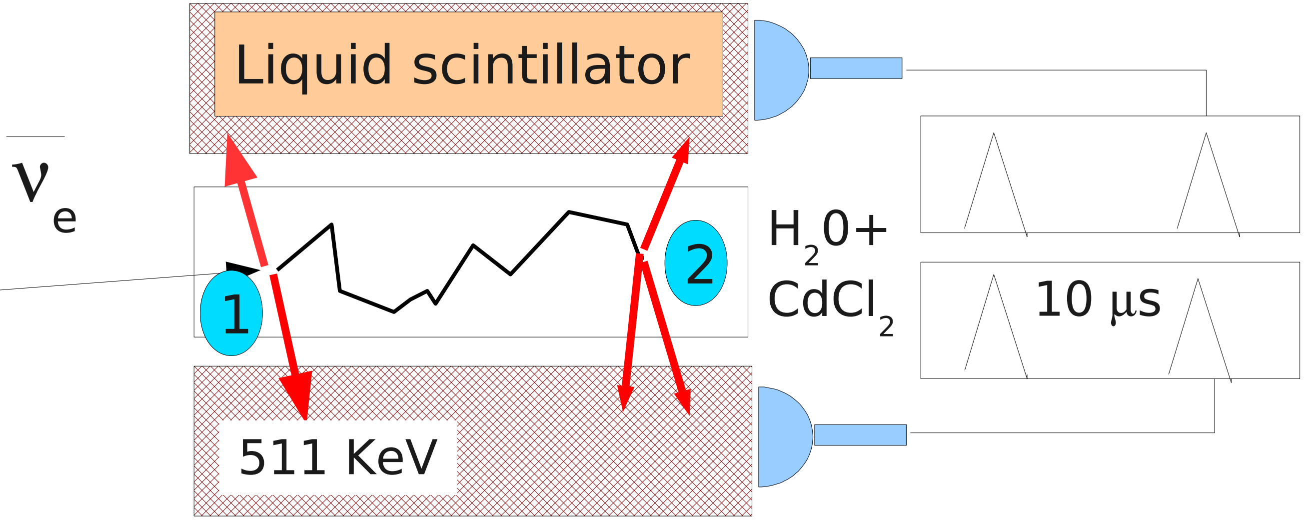
A nuclear reactor is the next best thing

Fission of U^{235} produces a chain of β decays

Reactor on – Reactor off = 2.88 +/- 0.22 hr^{-1}
σ = (11 +/- 2.6) x 10^{-44} cm^2
σ (Pred) = (5 +/- 1) x 10^{-44} cm^2



Savannah River
(sort of)

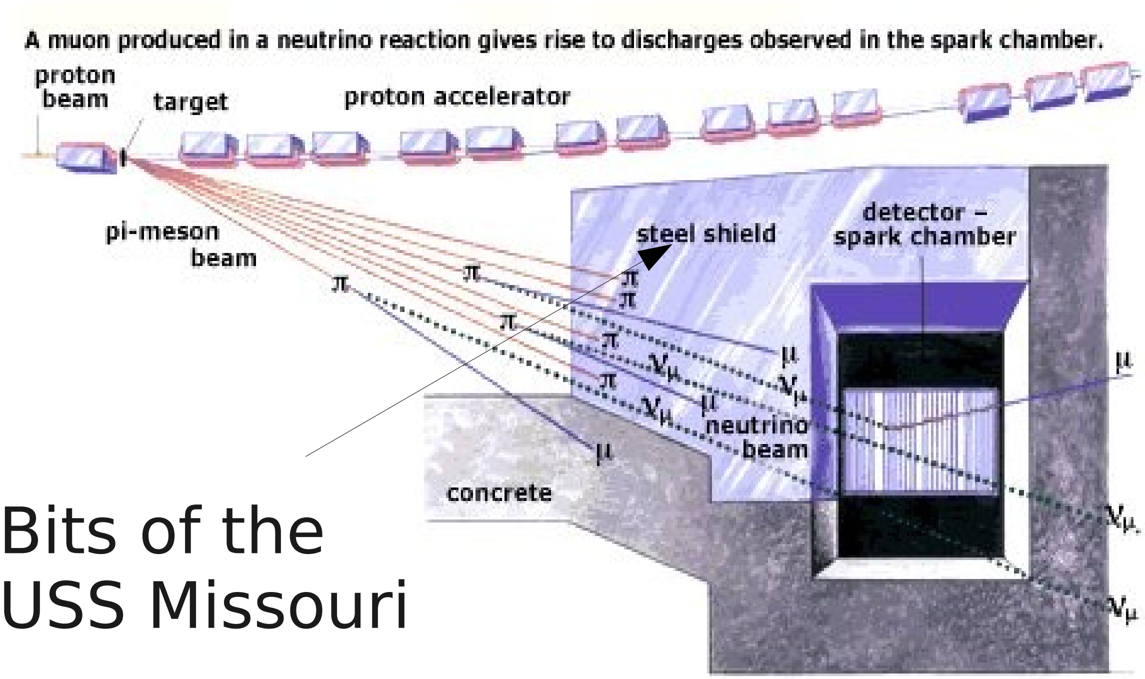


1. $\nu_e + p \rightarrow e^+ + n$
2. Neutron capture on Cd

From Zuber

Neutrinos come in flavours!

- Up to 1962, only the electron neutrino had been detected – and hence only the “neutrino” existed.
- Suspicions were strong that more were out there
- In 1962, Schwartz, Steinberger and Lederman presented evidence for the muon neutrino and built the very first neutrino beam!



A muon produced in a neutrino reaction gives rise to discharges observed in the spark chamber.

Bits of the USS Missouri

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

$$\nu_\mu + n \rightarrow \mu^- + p \quad \text{OK}$$

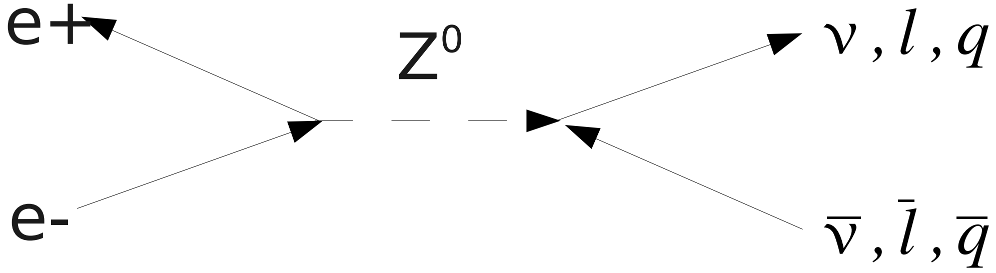
$$\nu_\mu + n \rightarrow e^- + p \quad \cancel{\text{OK}}$$

The State of Play 1962

Flavour	Mass (GeV/$c^{2)}$	Electric Charge
ν_e	< 1 x 10-8	0
electron	0.000511	-1
ν_μ	< 0.0002	0
muon	0.106	-1
tau	1.7771	-1

How many neutrinos do we expect to find?

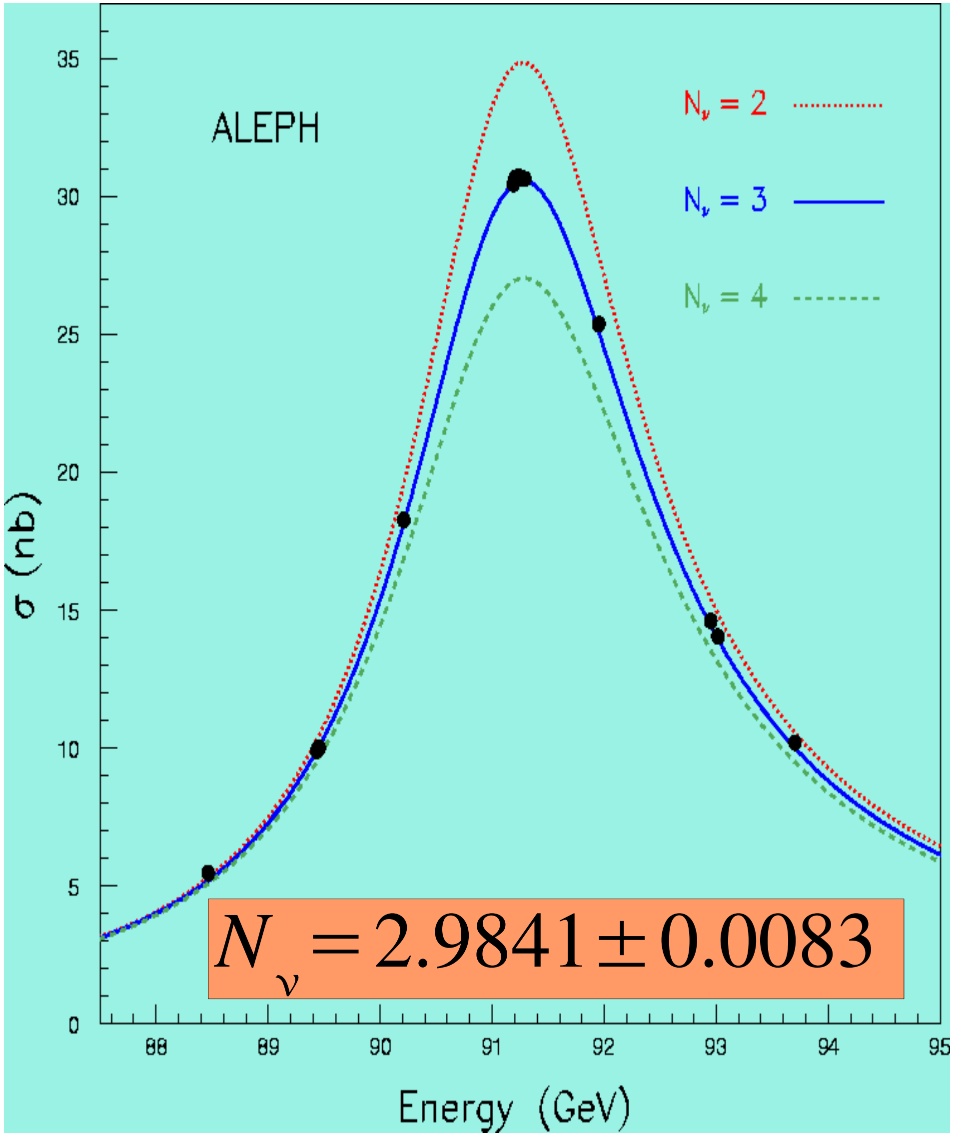
The Number of light neutrinos



$$\Gamma_Z = \sum \Gamma_{q\bar{q}} + 3\,\Gamma_{l\bar{l}} + N_\nu\,\Gamma_{\nu\bar{\nu}}$$

Discovery of Z0 allowed a measurement of the number of light neutrinos since the Z0 can decay to a neutrino and antineutrino

NB Mass of ν < $m_Z/2$ ~ 46 GeV



$N_\nu = 2.9841 \pm 0.0083$

The Tau Neutrino

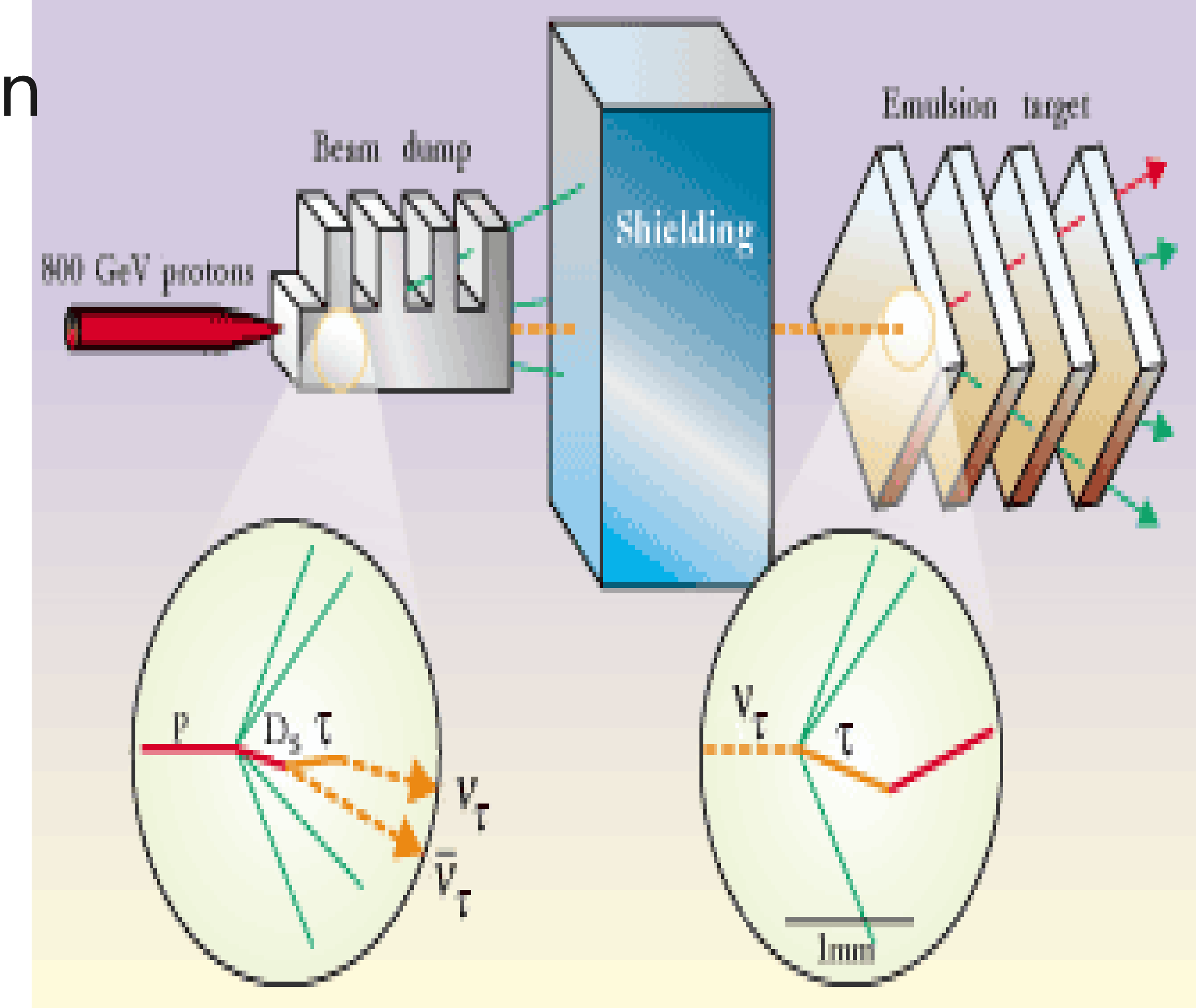
ν_τ was finally discovered by DONUT in 2000.

800 GeV protons on Tungsten produce D_s (=$c\bar{s}$) mesons

$$D_s \rightarrow \tau + \nu_\tau$$

$$\nu_\tau + N \rightarrow \tau + X$$

$$\tau \rightarrow \mu + \nu_\tau + \overline{\nu_\mu}$$



Neutrino properties and fallacies

Neutrino Properties

- Electrically neutral and interact only via the weak interaction.
- neutrinos are left-handed.
- Exist in (at least) 3 active flavours
- Are almost massless
- Are the most common fermions in the universe

- Is a neutrino it's own anti-particle (Majorana particle)?
- Are there sterile neutrinos?
- What is the absolute neutrino mass?
- Is there CP violation in the neutrino sector?
- Does the neutrino have a magnetic moment?
- Are they stable?

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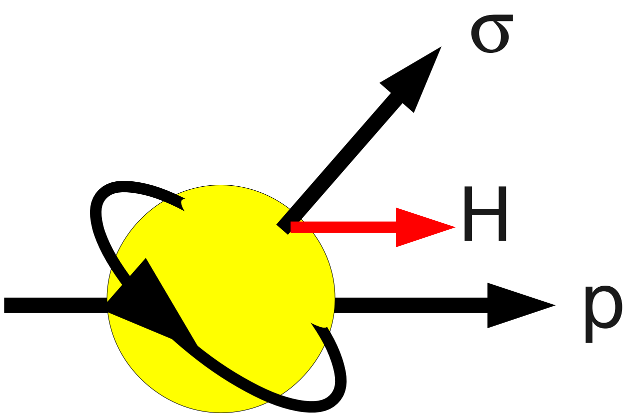
Helicity and Chirality

- *Helicity* is the projection of spin along the particles direction



$$\hat{H} = \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|}$$

H is not Lorentz Invariant unless particle is massless

Something is *chiral* if it cannot be superimposed on its mirror image

Not directly measurable but is Lorentz invariant

$$P_{+-} = \frac{(1\pm\Lambda)}{2} \rightarrow P_{L,R} = \frac{(1\pm\gamma_5)}{2}$$

Handedness ≠ Chirality

In the limit of *zero mass*, chirality = helicity
A massive left-handed particle may have both helicity states

Weak Interaction

- Until 1956 everybody assumed that the weak interaction, like the electromagnetic interaction, conserved parity

- This was found to be false (see Lee&Yang, Wu)

- Weak interaction maximally violates parity in that it only couples to left-handed chiral particles and right-handed chiral antiparticles

- This is the so-called V-A theory of weak currents

- This has implications for neutrinos

Implication for neutrinos

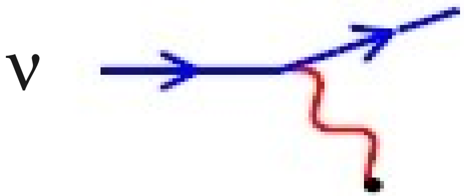
- Neutrinos only interact weakly through a V-A interaction
- If Neutrinos are massless then
  - Neutrinos are always left-handed (chiral) and have left-handed helicity
  - Antineutrinos are always right-handed (chiral) and have right-handed helicity
    - Because of ***production***
- If Neutrinos have mass then
  - It is possible to observe a neutrino with *right-handed* helicity (but NOT chirality)

$$P(\text{“wrong-sign” helicity}) \propto (m/E)^2$$

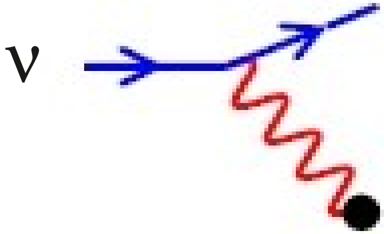
In which neutrinos reluctantly interact

A neutrino can see....

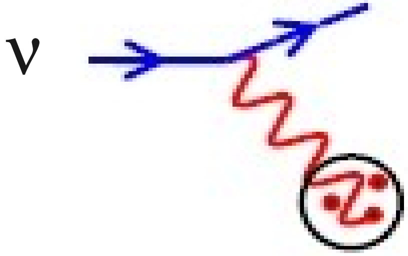
- Very low Q^2, $\lambda > r_p$, and scattering is off a “point-like” particle



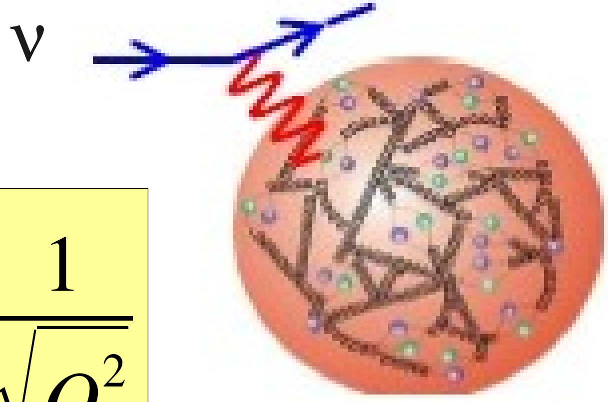
- Low Q^2, $\lambda \sim r_p$, scattering is off an extended object



- High Q^2, $\lambda < r_p$, can resolve quark in the nucleon



- Very High Q^2, $\lambda << r_p$, can resolve sea of quarks and gluons in nucleon

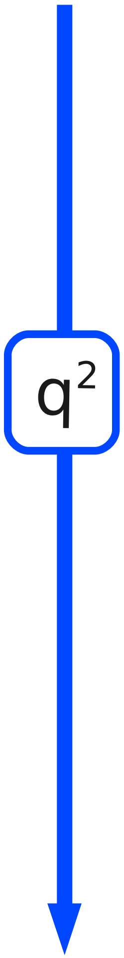


$$\lambda = \frac{1}{p} \sim \frac{1}{\sqrt{Q^2}}$$

Neutrino-Nucleon Interactions in a Nutshell

CC – $W^\pm$ exchange

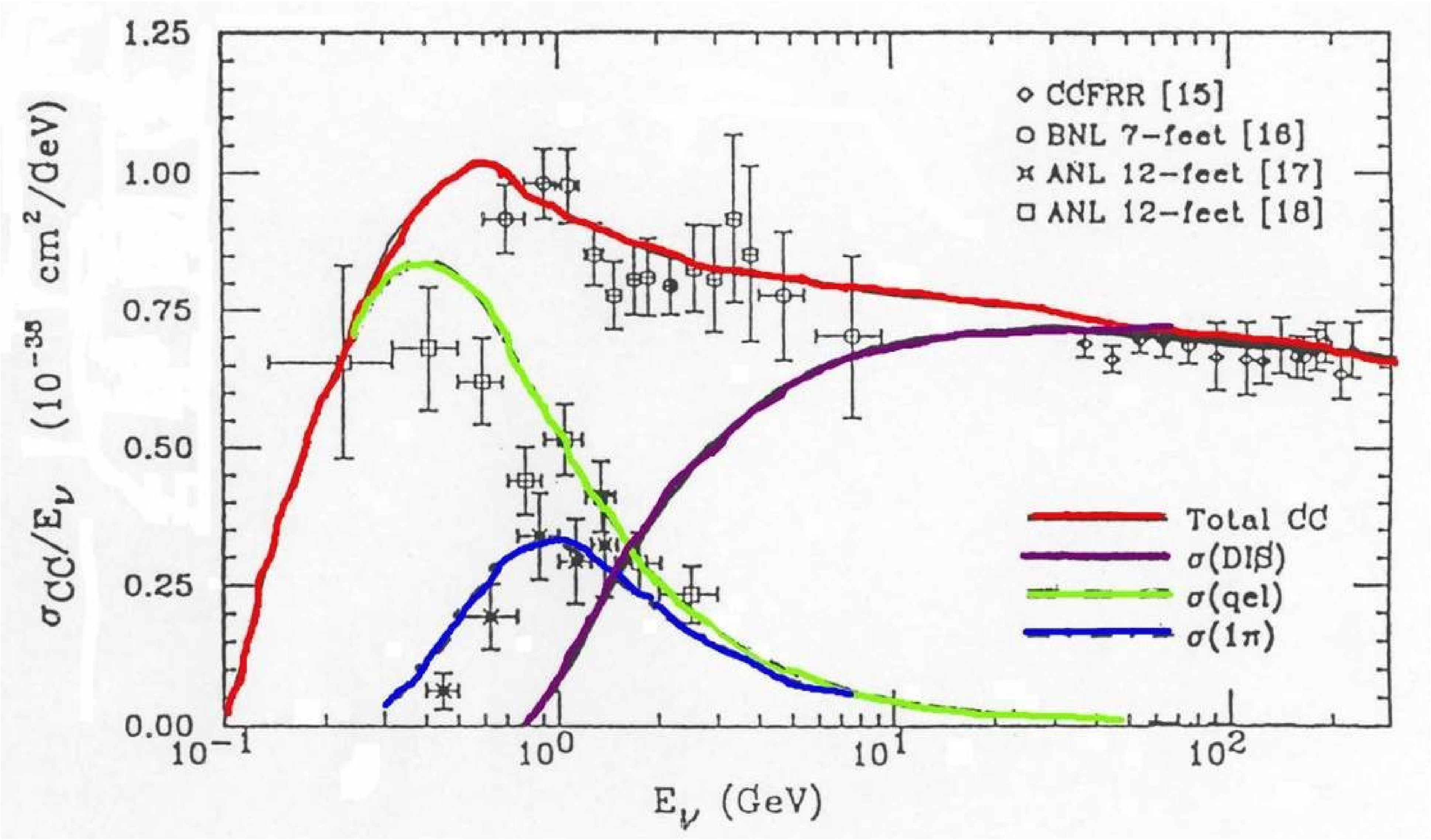
- Quasi-elastic Scattering
  - Target changes but no breakup
  - $\nu_\mu + n \rightarrow \mu^- + p$
- Coherent/Diffractive production
  - Target unchanged
  - $\nu_\mu + n \rightarrow \mu^- + n + \pi^+$
- Nuclear resonance production
  - Target goes to excited state and decays
  - $\nu_\mu + n \rightarrow \mu^- + p + \pi^0$ (N* or Δ)
  - $n + \pi^+$
- Deep Inelastic Scattering
  - Target breaks up
  - $\nu_\mu + \text{quark} \rightarrow \mu^- + \text{quark}'$



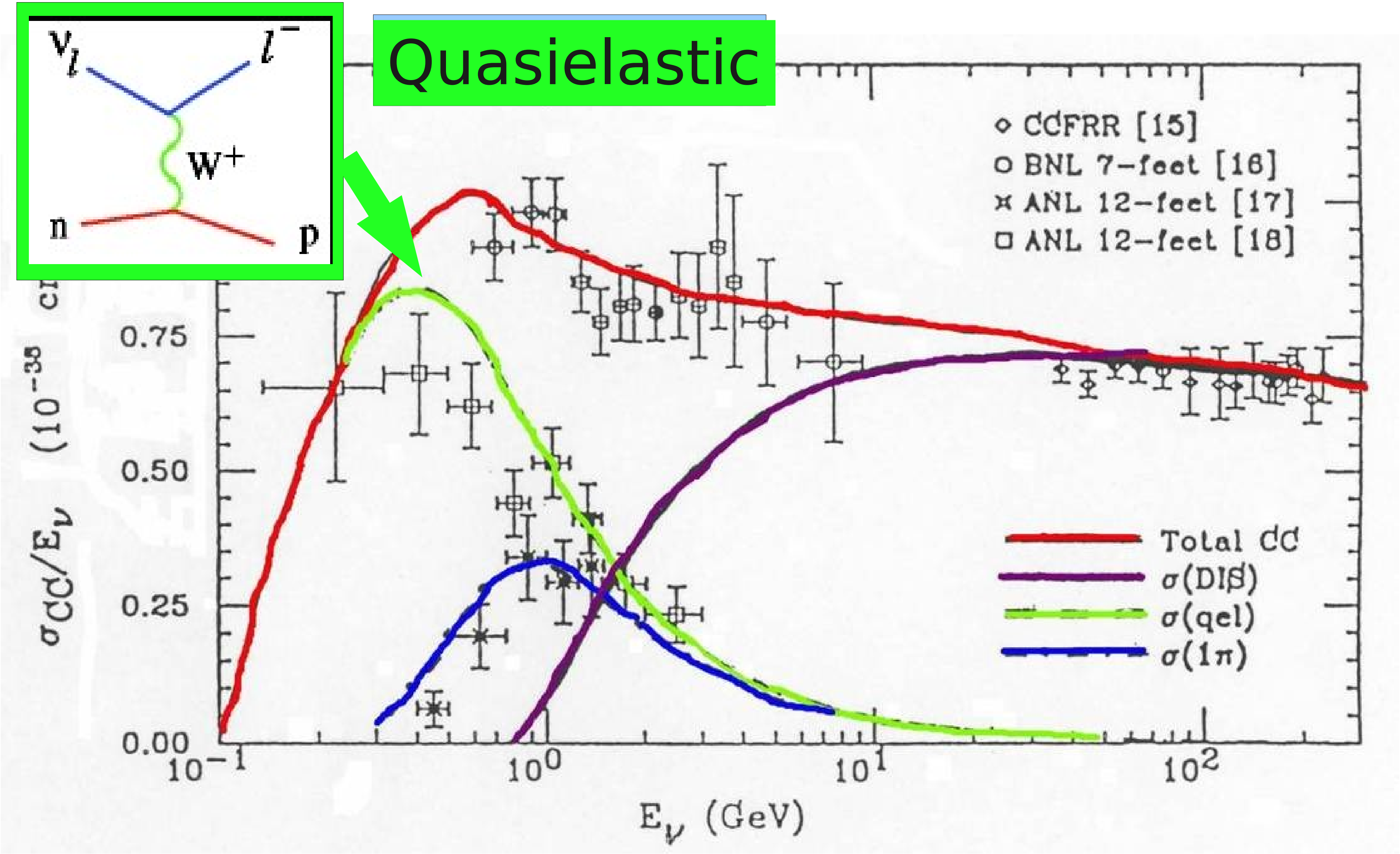
NC – Z^0 exchange

- Elastic Scattering
  - Target unchanged
  - $\nu_\mu + n \rightarrow \nu_\mu + n$
- Coherent/Diffractive production
  - Target unchanged
  - $\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0$
- Nuclear resonance production
  - Target goes to excited state and decays
  - $\nu_\mu + N \rightarrow \nu_\mu + N + \pi$ (N* or Δ)
- Deep Inelastic Scattering
  - Target breaks up
  - $\nu_\mu + \text{quark} \rightarrow \nu_\mu + \text{quark}$

Neutrino Cross Sections



Neutrino Cross Sections



Quasielastic

Experimental signature

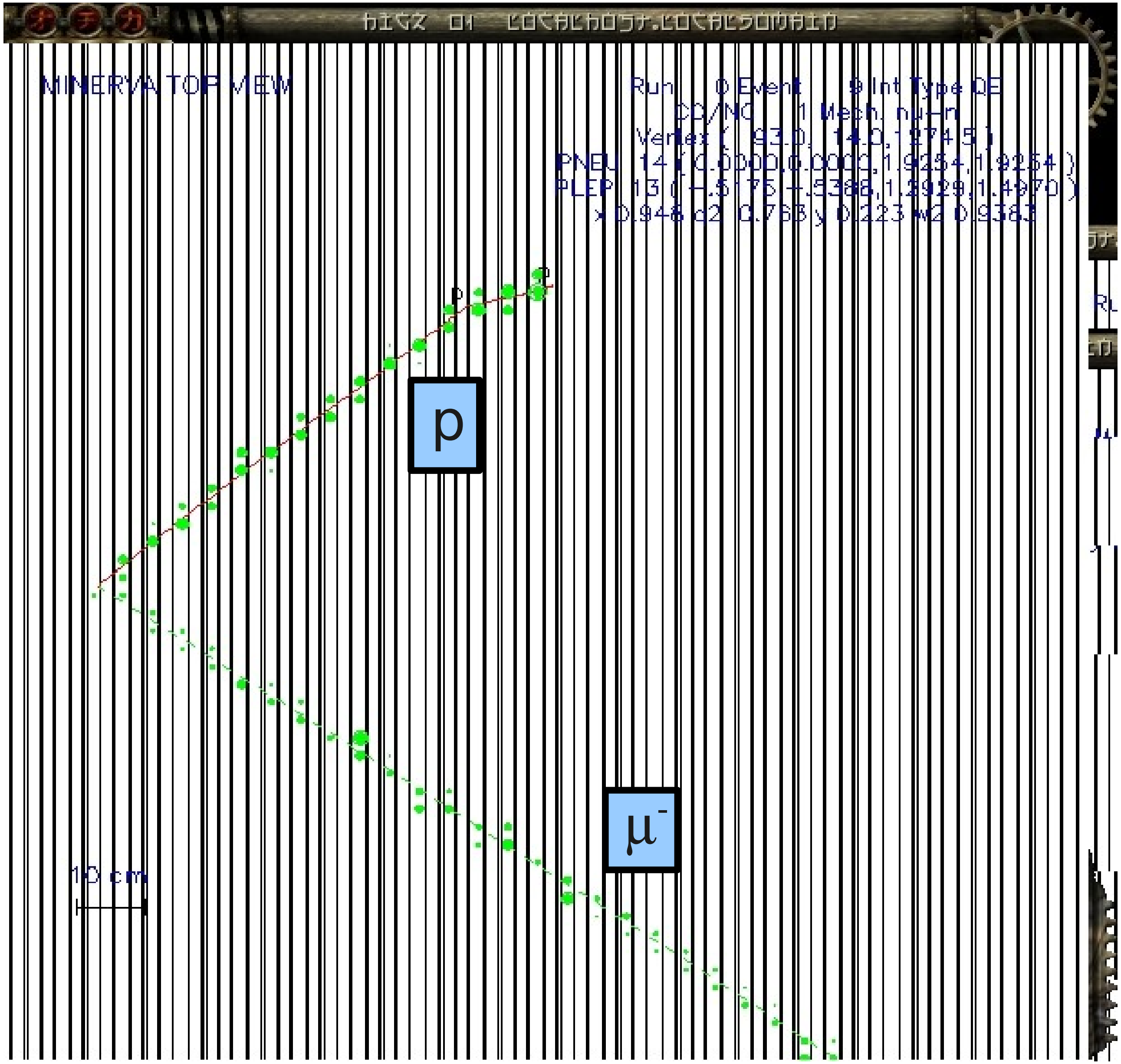
$$\boxed{\nu_\mu + n \rightarrow \mu^- + p}$$

$$\overline{\nu}_\mu + p \rightarrow \mu^+ + n$$

$$\overset{(-)}{\nu} + N \rightarrow \overset{(-)}{\nu} + N$$

Proton id from dE/dx
Muon id from range
Two-body so angles are known if E_μ is known

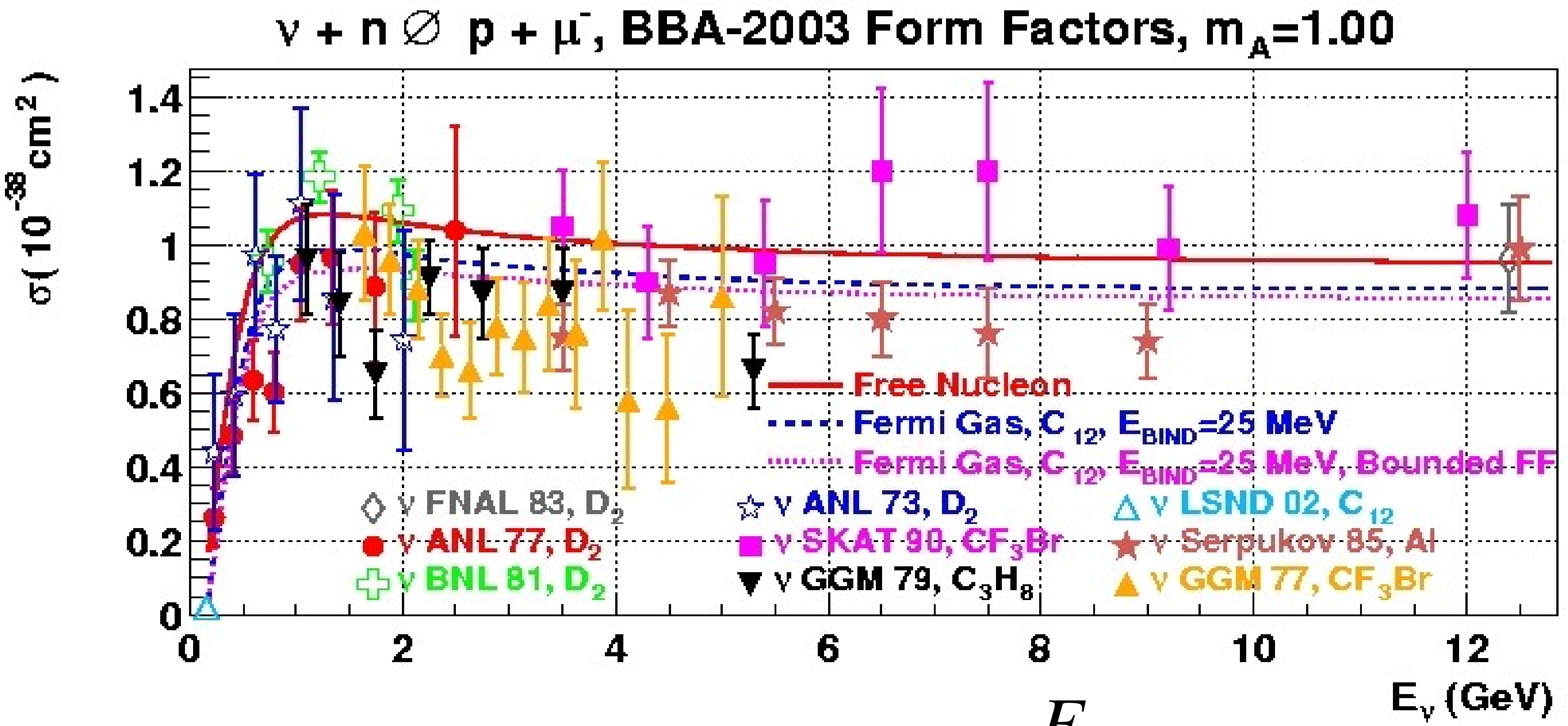
$$\boxed{E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}}$$



```
MINERVA TOP VIEW
Run 0 Event 9 Int Type QE
CC/NC 1 Mech. nu-n
Vertex ( 93.0, 14.0,1274.5 )
PNEU 14 ( 0.0000,0.0000,1.9254,1.9254 )
PLEP 13 ( -.5175,-.5388,1.2929,1.4970 )
x 0.948 q2 0.763 y 0.223 w2 0.9383
```

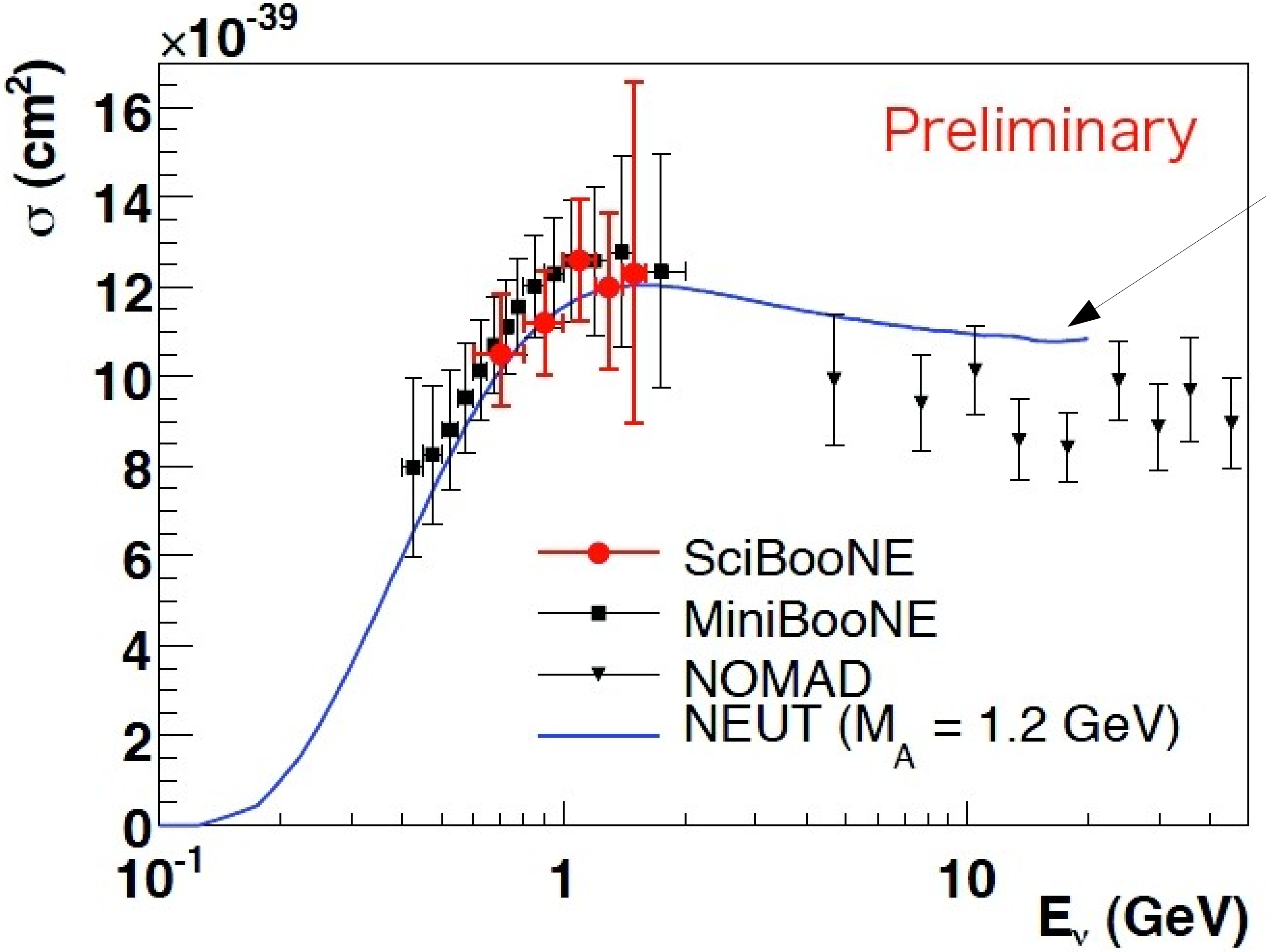
Problems with QE

The CC QE process is the best known neutrino process occurring at a few GeV



$$\sigma_{QE} \sim 0.975 \times 10^{-38} \left(\frac{E_\nu}{1\, GeV} \right) cm^2$$

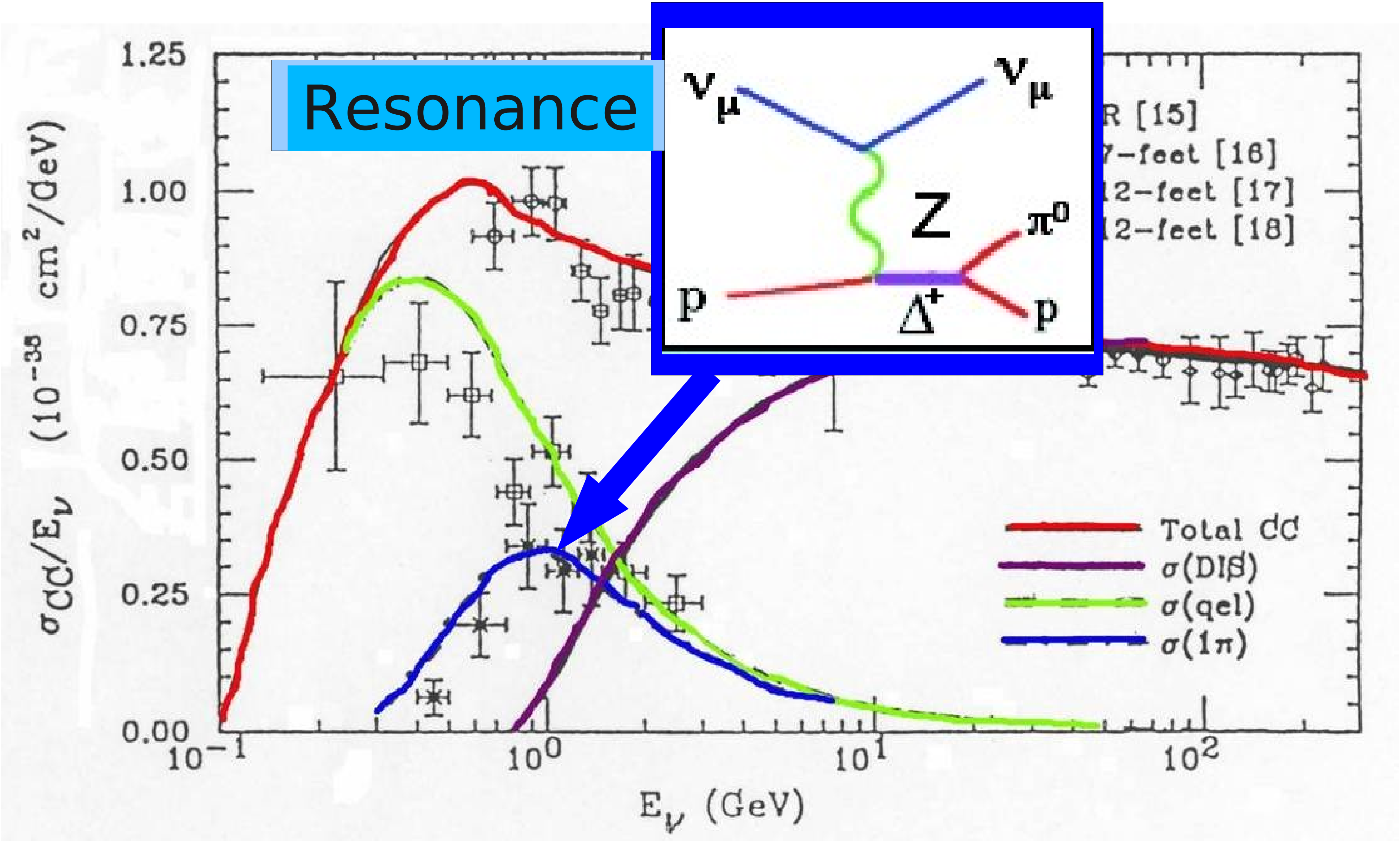
It's getting better



Note tension between low and high energy measurements

Y. Nakajima *NuInt11*

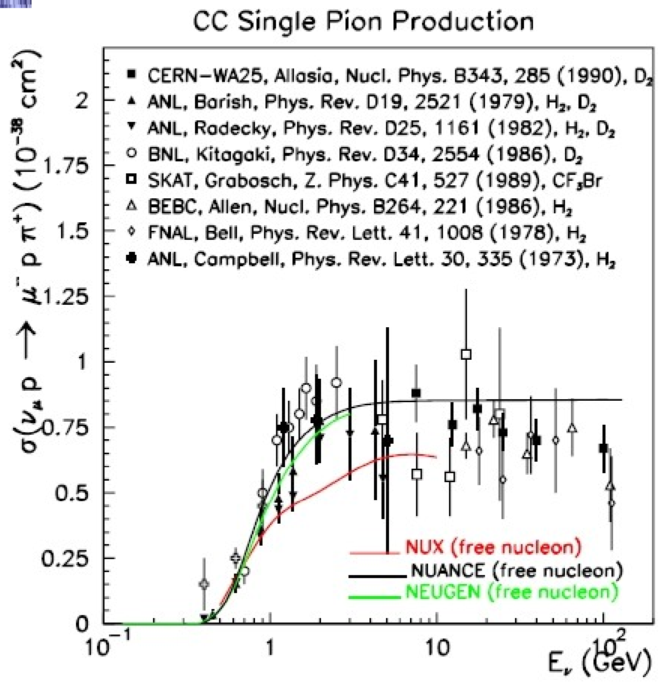
Neutrino Cross Sections

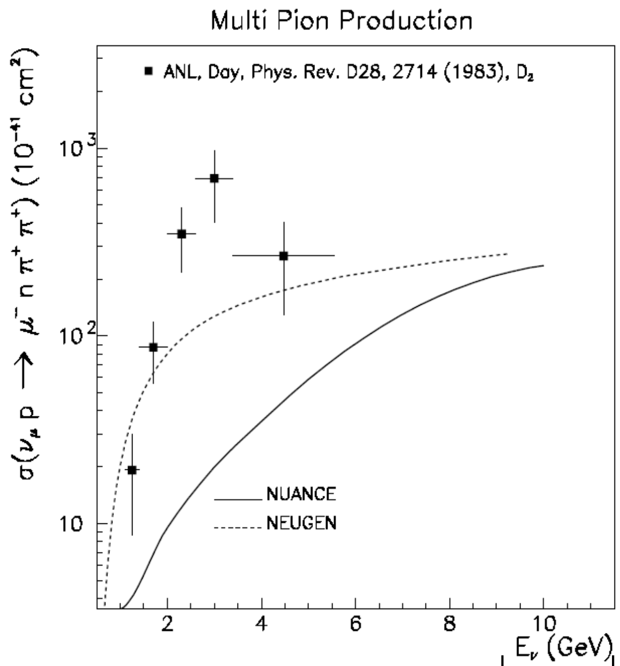


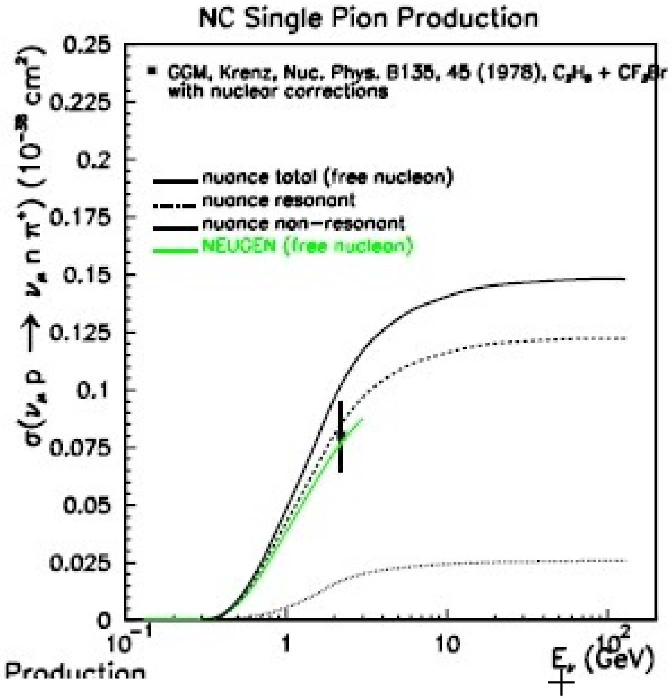
Resonance

Resonance Region Data

The data is impressively imprecise





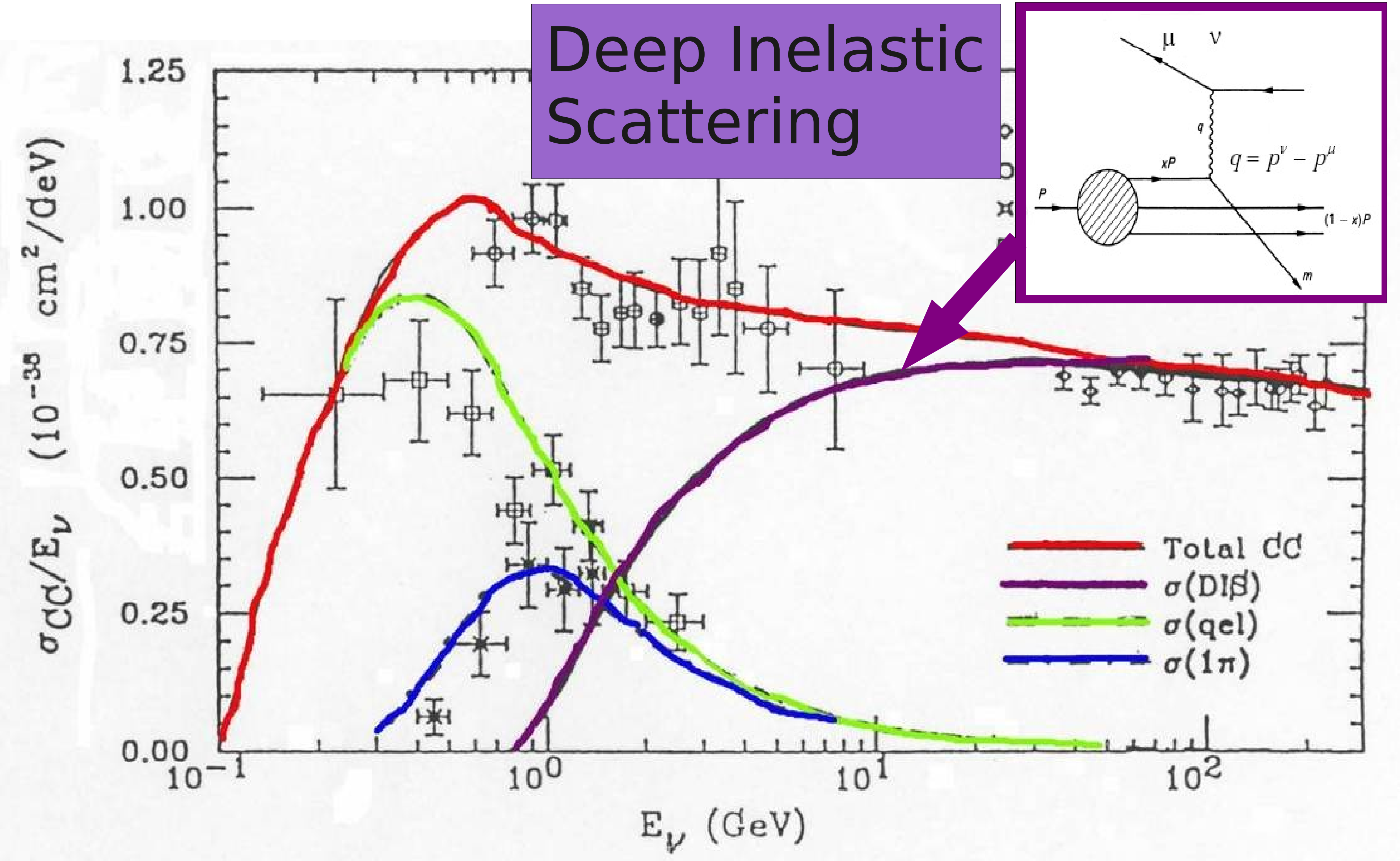


$\nu_\mu p \rightarrow \mu^- p \pi^+$ $\quad$ $\nu_\mu p \rightarrow \mu^- n \pi^+ \pi^+$ $\quad$ $\nu_\mu p \rightarrow \nu_\mu n \pi^+$

Added complication that the final state pions can (i) scatter (ii) be absorbed (iii) charge exchange within the nucleus before being observed (iv) nucleons rescatter producing π

$\pi^+ n \rightarrow \pi^0 p$

Neutrino Cross Sections



Deep Inelastic Scattering

Problems we haven't really mentioned

1. We are assuming that the initial target nucleon is just sitting still before interaction. Actually in the nucleus it has some initial momentum distribution.

The Fermi momentum modifies the scattering angles and momentum spectra of the outgoing final state

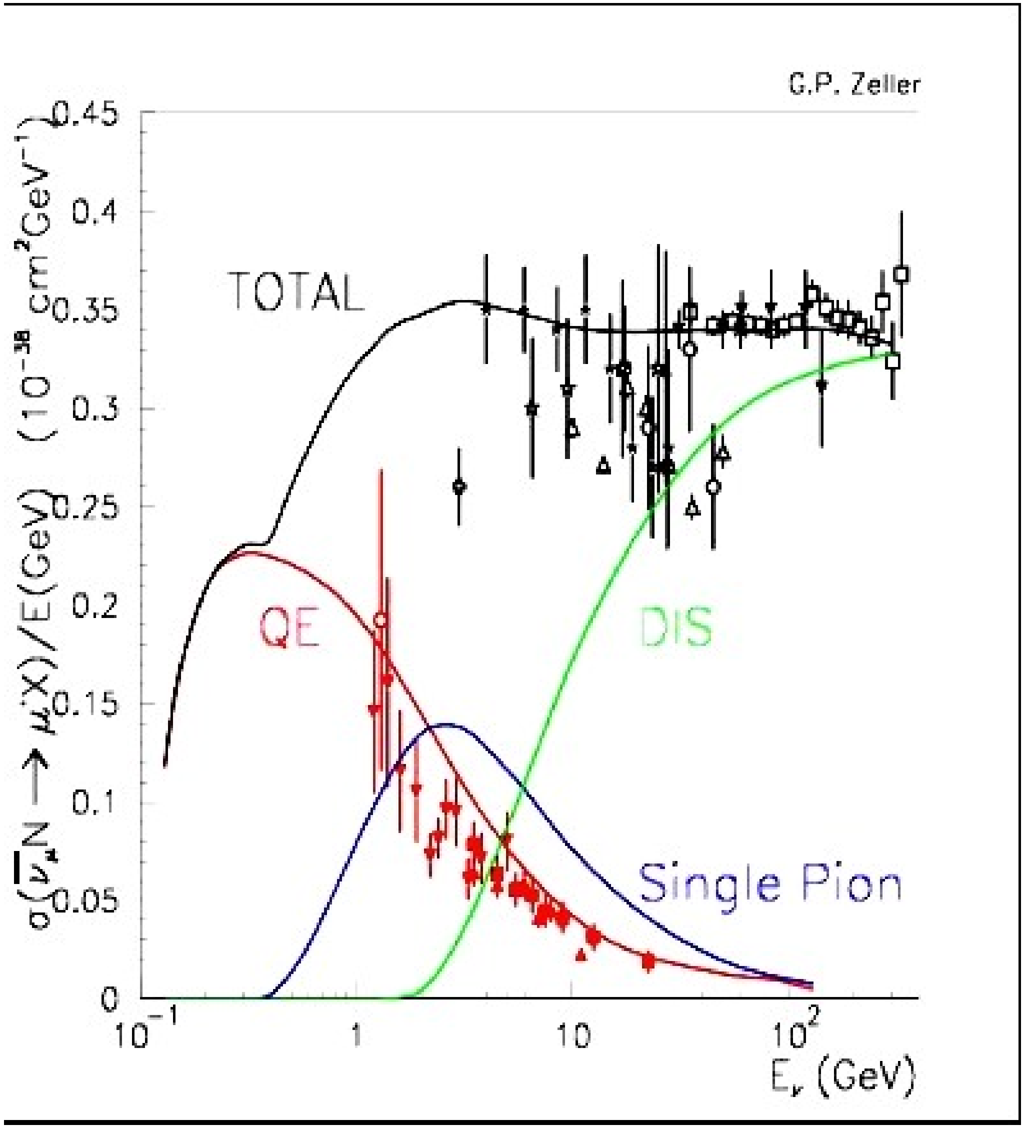
2. The outgoing final state can interact with the target nucleus.

This nuclear re-interaction affects the outgoing nucleon momentum direction and charge (through charge exchange interactions)

Theoretical uncertainties are **large**

- At least 10%
- If precise knowledge is needed for a particular target (e.g. Water, hydrocarbon) then measurements are needed
- Last measurements taken in the '70s

World Data for Antineutrinos

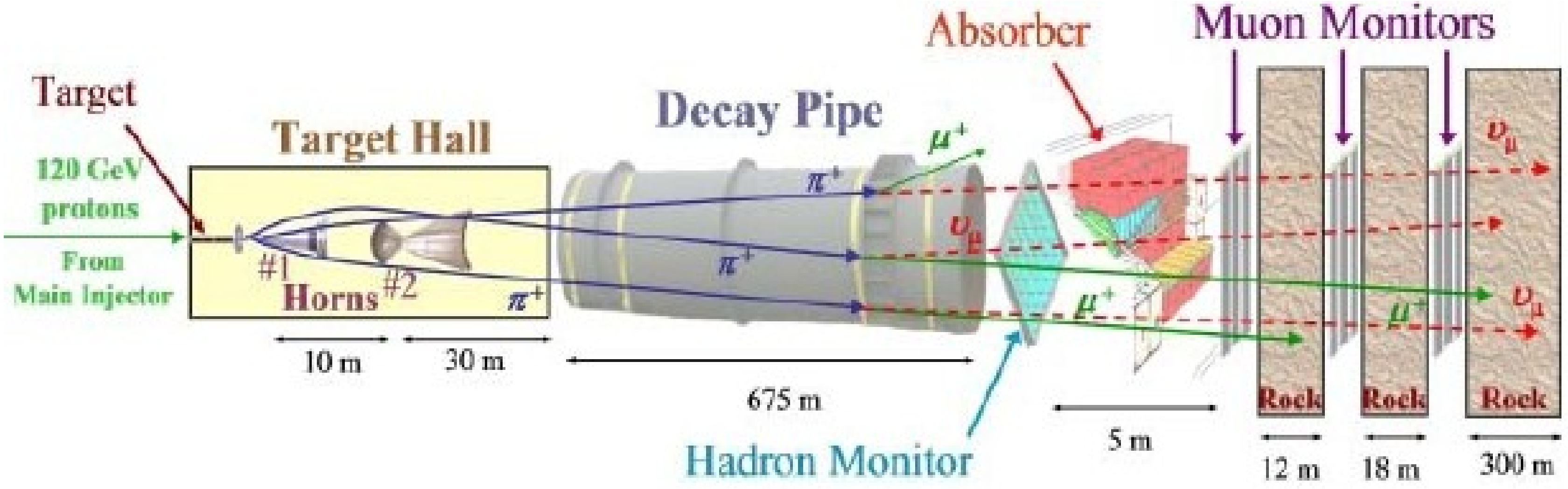


Neutrino experiments are hard!

“..in an ordinary way I might say that I do not believe in neutrinos. Dare I say that experimental physicists will not have sufficient ingenuity to make neutrinos”

Sir Arthur Eddington

How to make a neutrino beam



protons π/K μ,π,K,ν_e,ν_μ ν_μ,ν_e

- Each part of the beamline must be designed with many tradeoffs in mind
- Major uncertainty in beam is the production of π/K in p-target interactions
- Total flux uncertainties ~ 20%

Proton Beam

- Number of pions $\propto$ total number of protons on target (POT) times proton energy

- The higher energy neutrino beam you want, the higher energy proton beam you need.

Source	p Energy (GeV)	p/year	Power (MW)	Neutrino Energy
KEK (Japan)	12	1.0E+20	0.01	1.4
FNAL Booster	8	5.0E+20	0.05	1
FNAL Main Injector	120	2.5E+20	0.25	3.0-17.0
CNGS (CERN)	400	4.5E+19	0.12	25
J-PARC (Japan)	40	1.1E+21	0.75	0.8

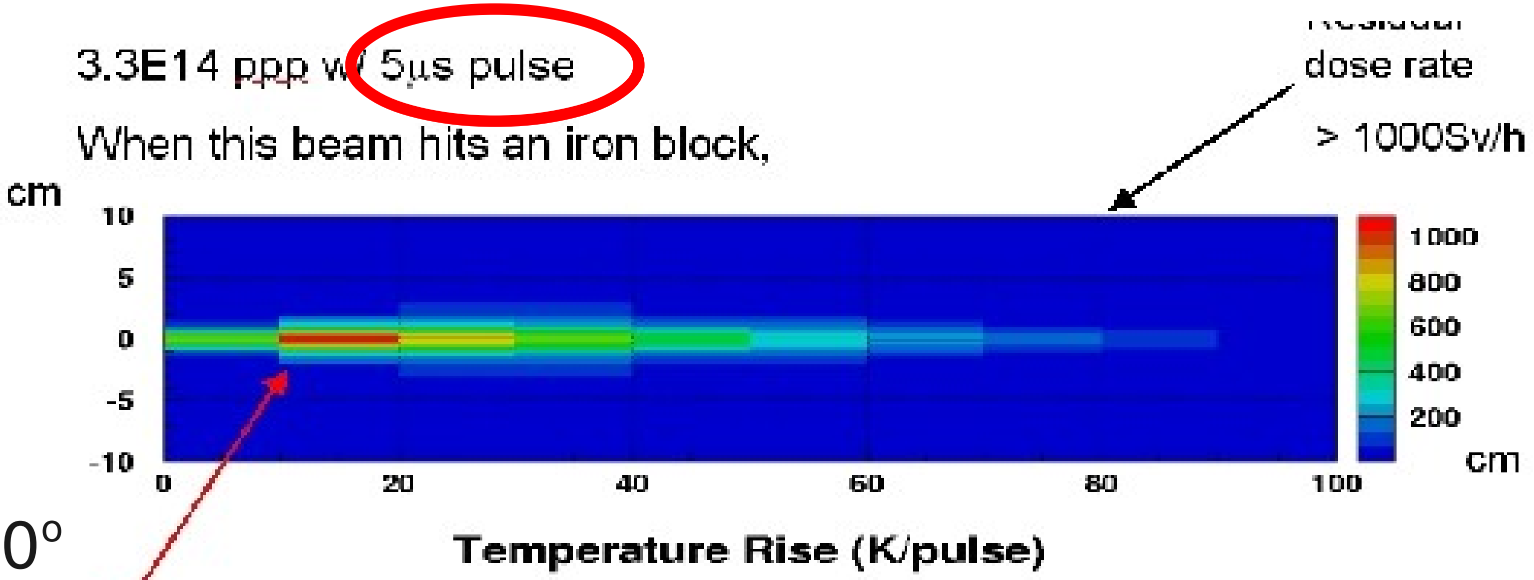
Targetry

Have to balance competing needs

- The longer the target, the higher the probability that a proton will interact (good)
- But more secondary particles will scatter (bad)
- The more protons interact the hotter the target will get (bad)
- The wider the target the cooler it is (good) but more material to scatter secondaries (bad)

Low Z material (C, Be, Al) for heat properties
Usually around 50 cm to 1 m long
In small segments so that heating won't break the entire thing
Cooling systems needed (air, water, liquid helium)

Targetry



3.3E14 ppp w/ 5μs pulse

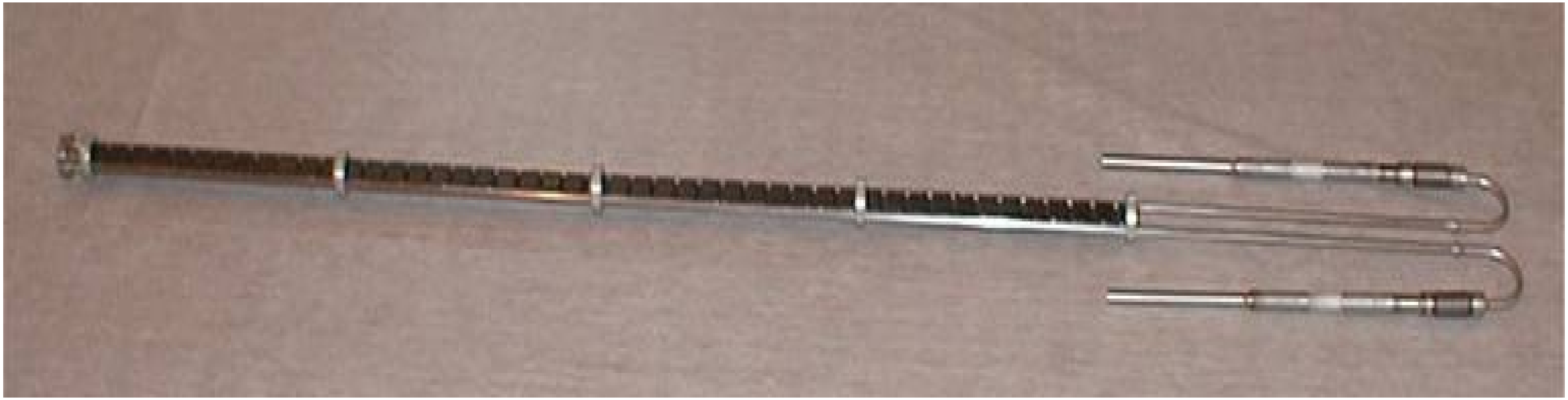
When this beam hits an iron block,

dose rate

> 1000Sv/h

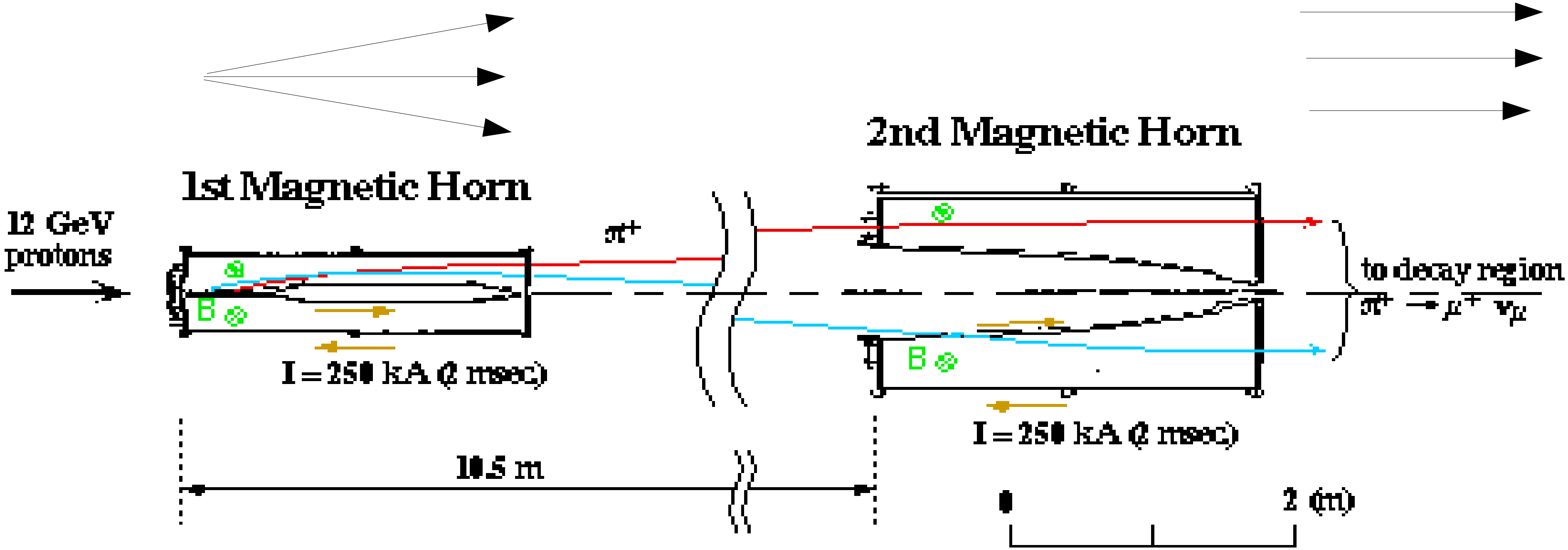
Temperature Rise (K/pulse)

1100°



Magnetic Horn system

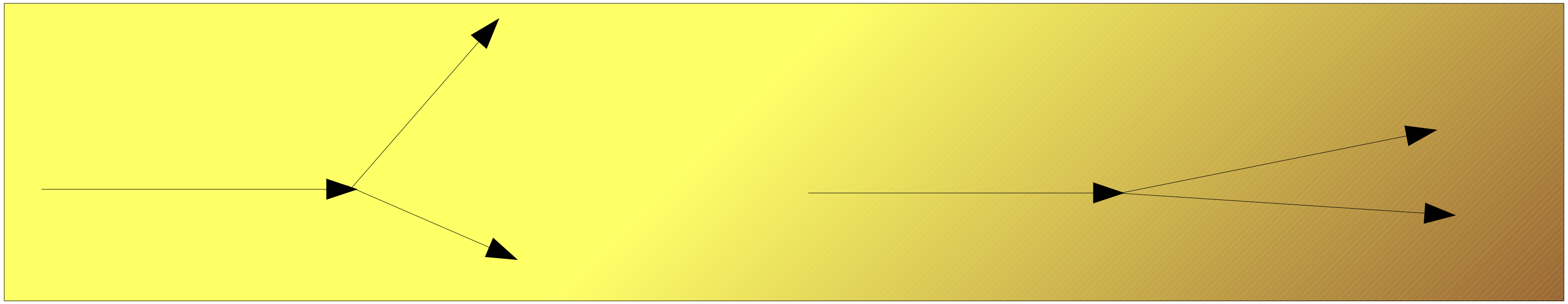
(for Long Baseline Neutrino Oscillation Experiment)



To give a 200 MeV transverse momentum kick to a pion requires a pulsed current of about 180 kA

Magnetic Horns

Decay Tunnel



Low Energy decays

High Energy decays

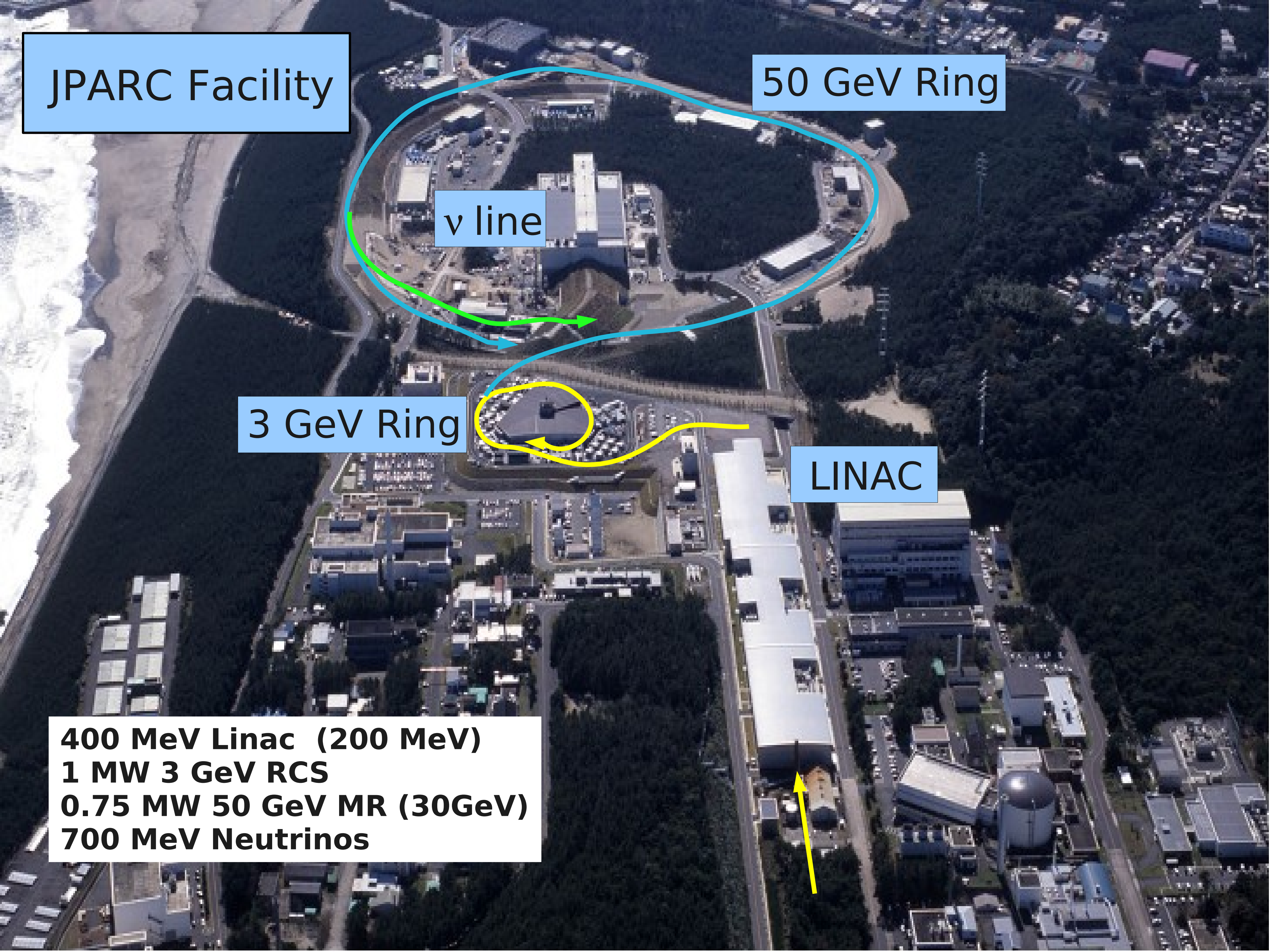
$$P(\pi \to \nu \mu) = 1 - e^{-t/\gamma \tau} = 1 - e^{-L m_{\pi} / E_{\pi} \tau}$$

Shorter tunnel, less pion decays

Longer tunnel, more pion decays, but muons decay to ν_e as well

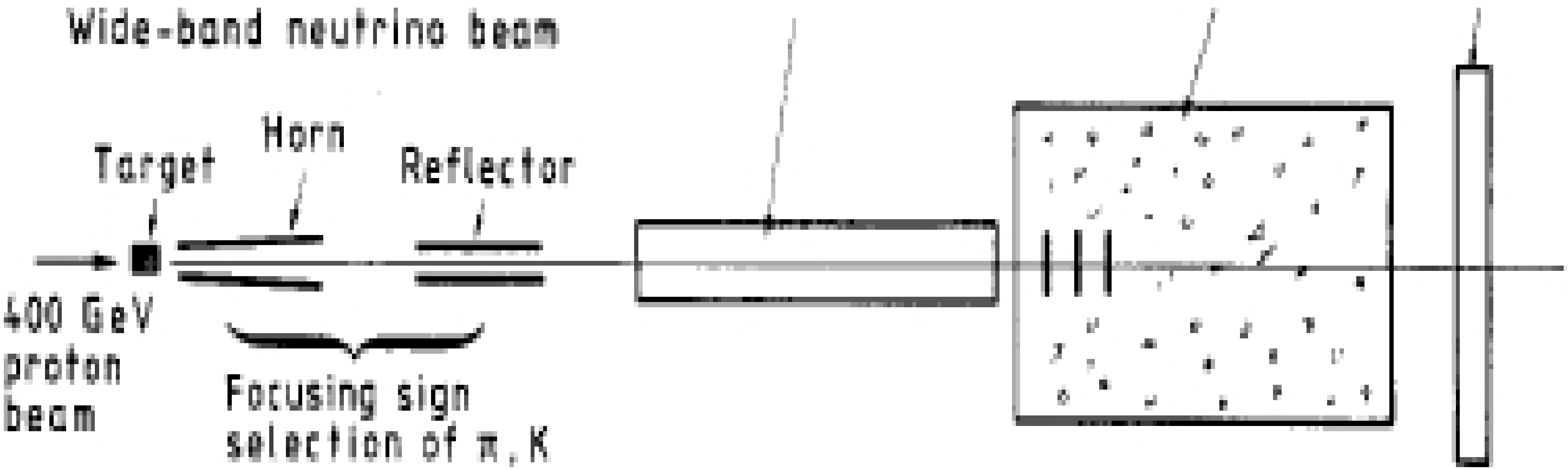
Vacuum? Then more material is needed to hold it. Air? Less material but interactions in decay pipe.

JPARC Facility

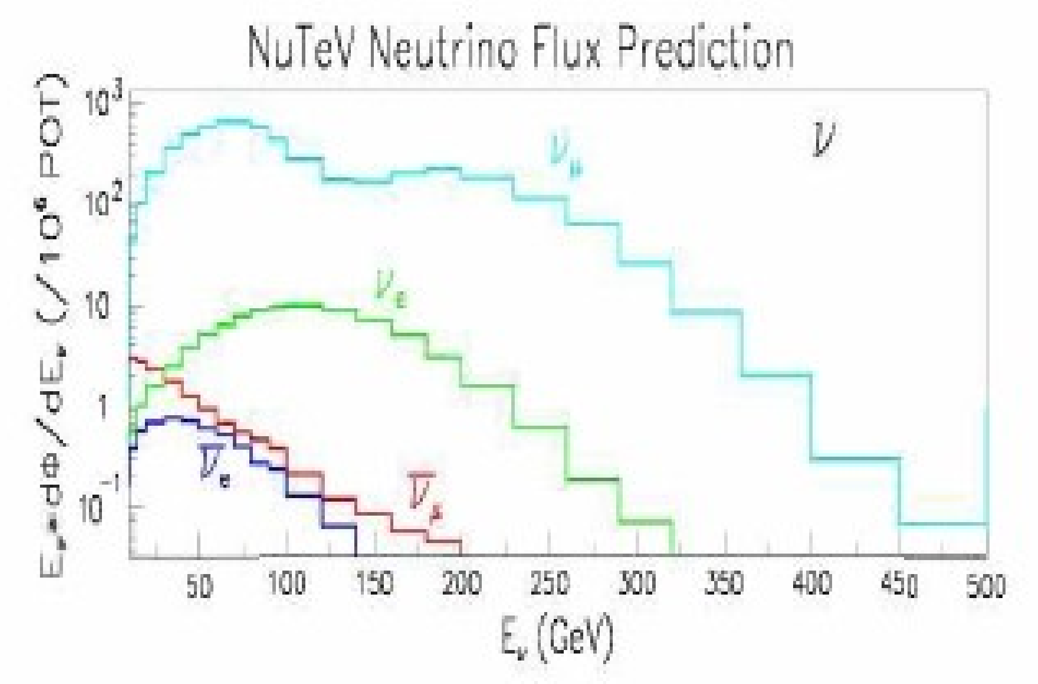


400 MeV Linac (200 MeV)
1 MW 3 GeV RCS
0.75 MW 50 GeV MR (30GeV)
700 MeV Neutrinos

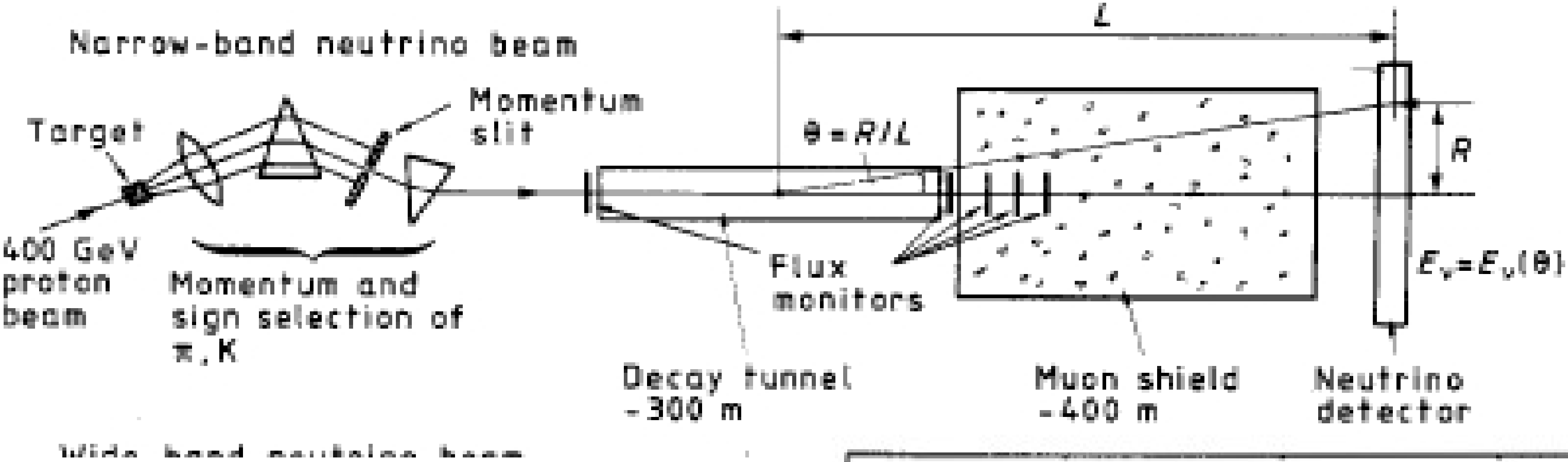
Wide band beams



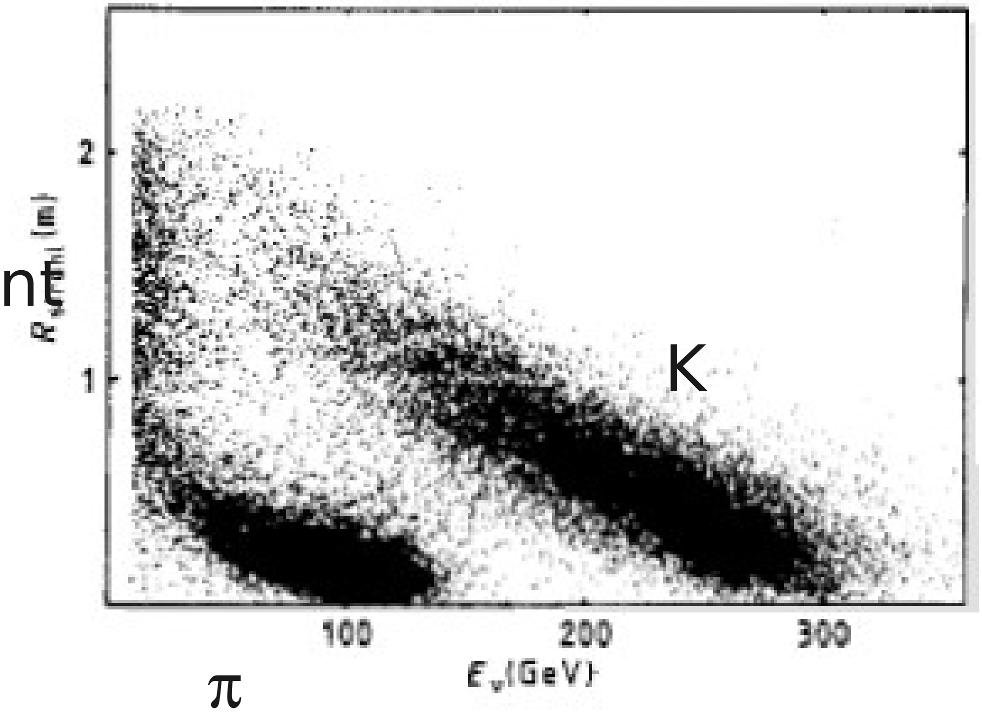
Large flux of neutrinos
Very hard to predict
(and measure) neutrino flu
Spectrum is a function
radius and decay point



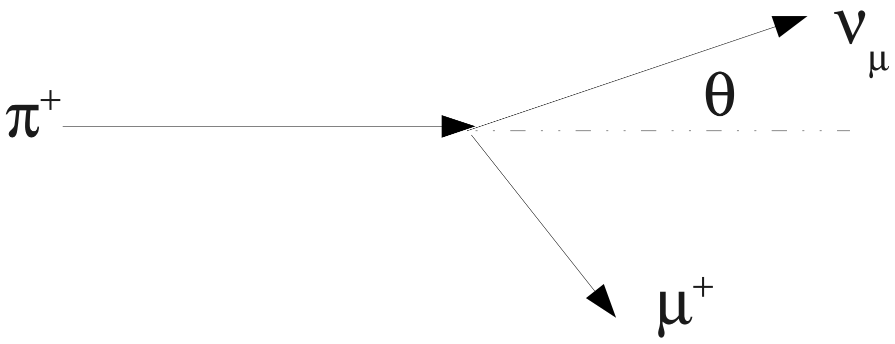
Narrow Band Beams



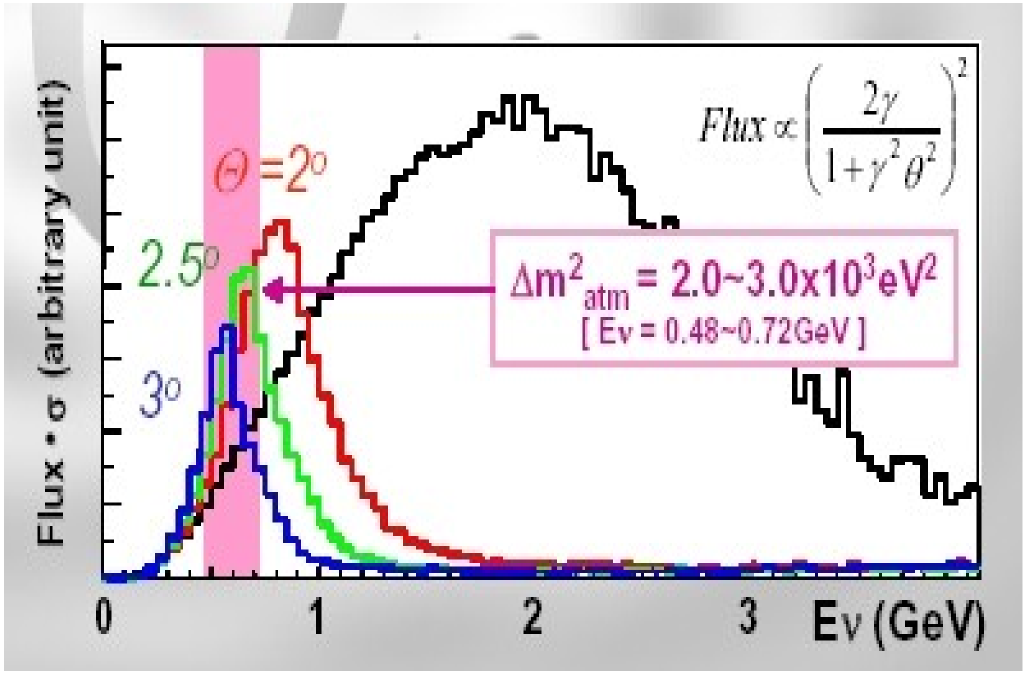
Flat flux (easy to predict)
Beam can be tuned to different energies
flux is 100 times lower than WBB

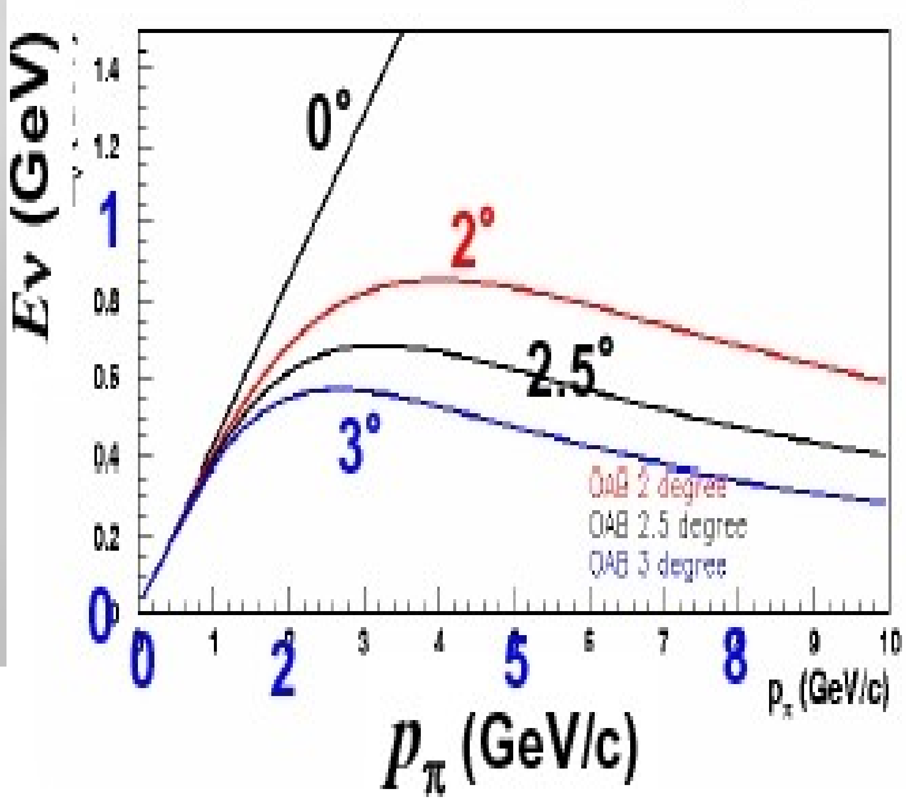


New idea : Off-axis beams



$$E_\nu = \frac{0.43\,E_\pi}{1+\gamma^2\theta^2} \qquad \gamma = \frac{E_\pi}{m_\pi}$$





Neutrino Detectors

So, you want to build a neutrino detector?

- How many events do you need to do the physics?
  - Determines detector mass
  - Determines the target type
- What kind of interaction? ν_e, ν_μ, CC, NC?
- What do you want to measure?
  - Energy? Final state particles? This influences detector technology
- What sort of backgrounds do have to deal with?
  - More influence on technology – usually conflicting with signal requirements.
- How much ca$h do you have?

Neutrino Detectors

- No neutrino colliders – detector IS the target
- Low cross section implies large mass and hence cheap material
- Neutrinos interact everywhere – vertex can be anywhere
- Neutrinos interact in matter - so final state is subject to nuclear potentials
- Need to identify charged lepton to separate NC and CC and neutrino flavour
- Measurement of energy and scattering angle of charged lepton
- Measurement of total hadronic energy
- Identification of single hadrons for hadronic studies

No experiment can satisfy all these requirements
Most experiments fall into one of a few types

Types of detectors

- Radiochemical experiments
- Water (H_20 or D_20) experiments
- Scintillator detectors
- Tracking calorimeters

Radiochemical Experiments

This techniques uses the production of radioactive isotopes.

Davis-Pontecorvo experiment was the first attempt to use this to look at solar neutrinos

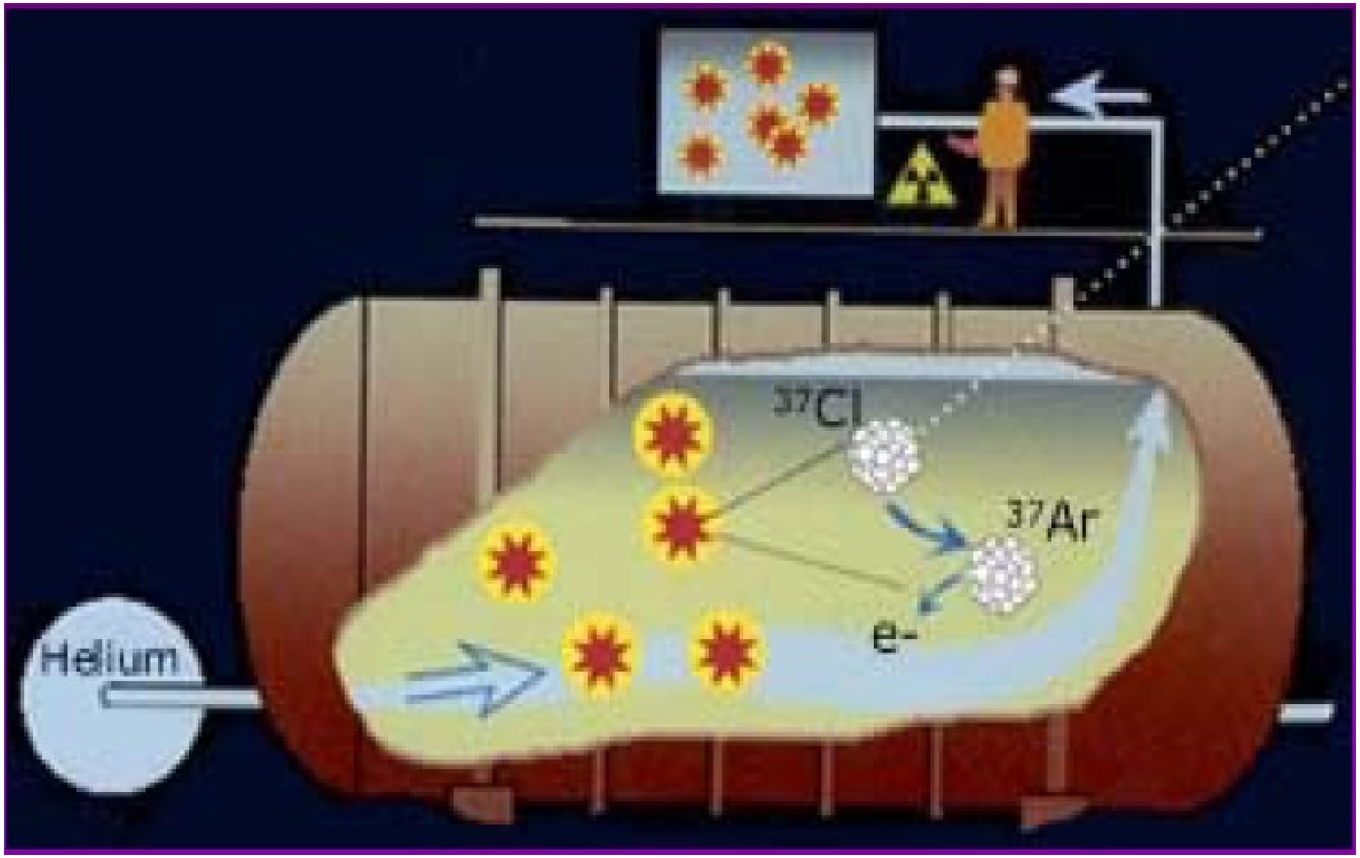
$$\nu_e + Cl^{37} \rightarrow Ar^{37} + e^- \qquad \nu_e + Ga^{71} \rightarrow \mathrm{Ge}^{37} + e^-$$

The isotopes Ar or Ge are radioactive. In this type of experiment the isotopes are chemically extracted and counted using their decay

Disadvantage is that there is no information on interaction time or neutrino direction, and only really generates “large” counte rates for low energy neutrinos (in the MeV range)

The Davis Experiment

The very first solar neutrino experiment in the Homestake mine in South Dakota



615 tonnes of Ccl4
Ran from 1968
Still running!

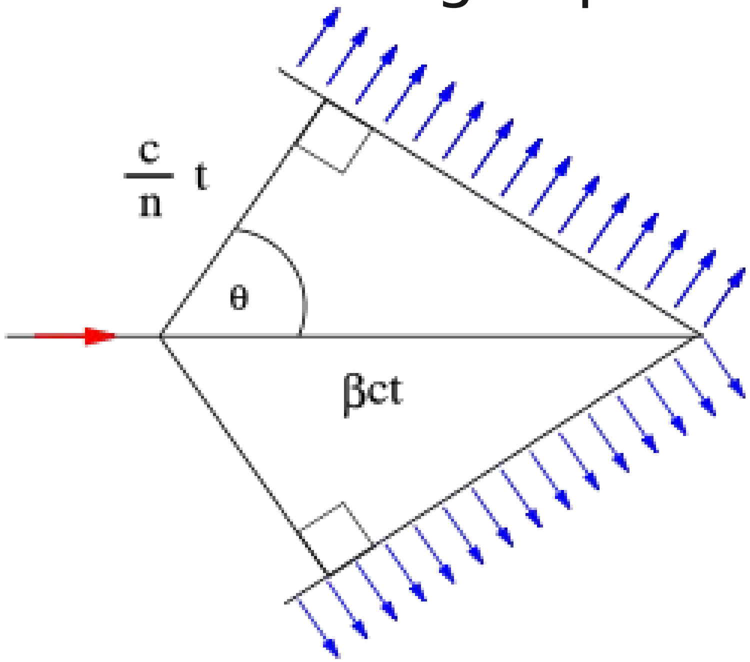
Individual argon atoms are captured and counted.

1 atom per 2 days.

Threshold : 814 keV

Water Experiments

Water is a very cheap target material – these experiments detect charged particles using Cerenkov radiation.

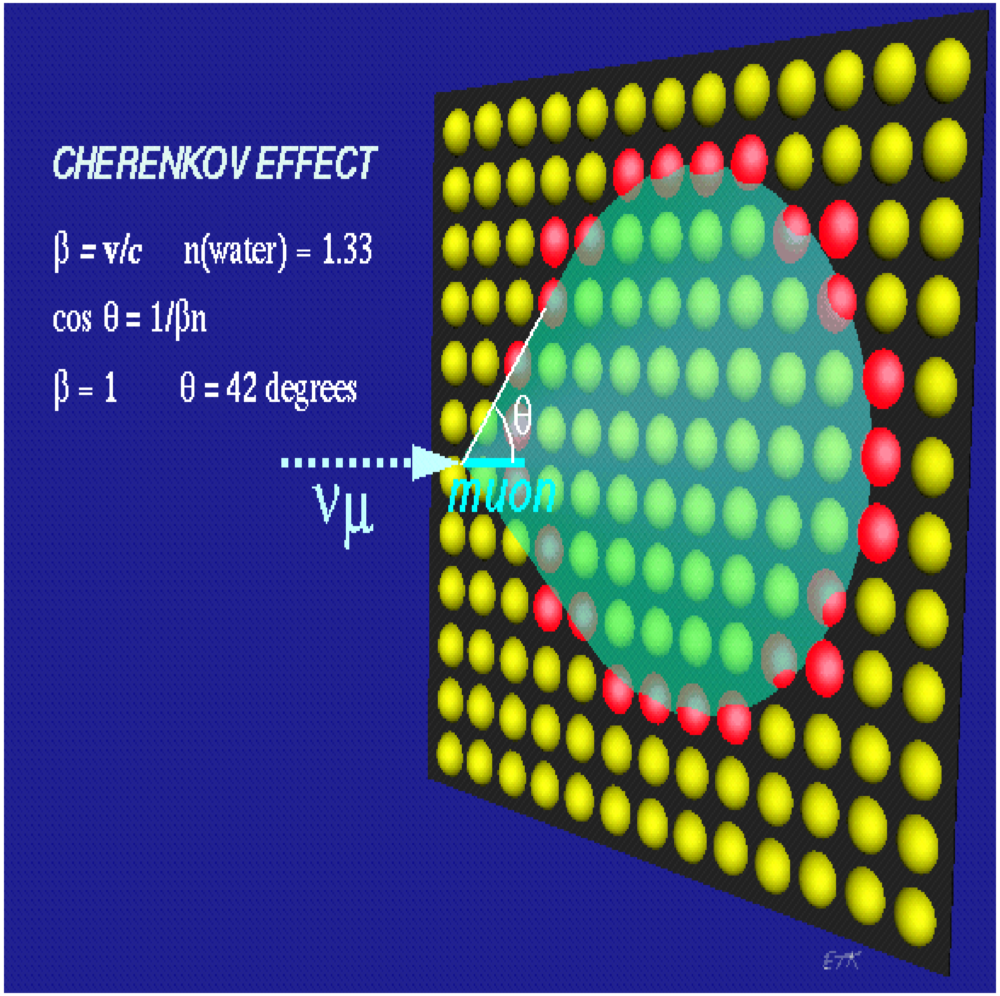


If a charged particle moves through a material with β > 1/n it produces an EM shockwave at a particular angle.

$$\cos\theta = 1/\beta n$$

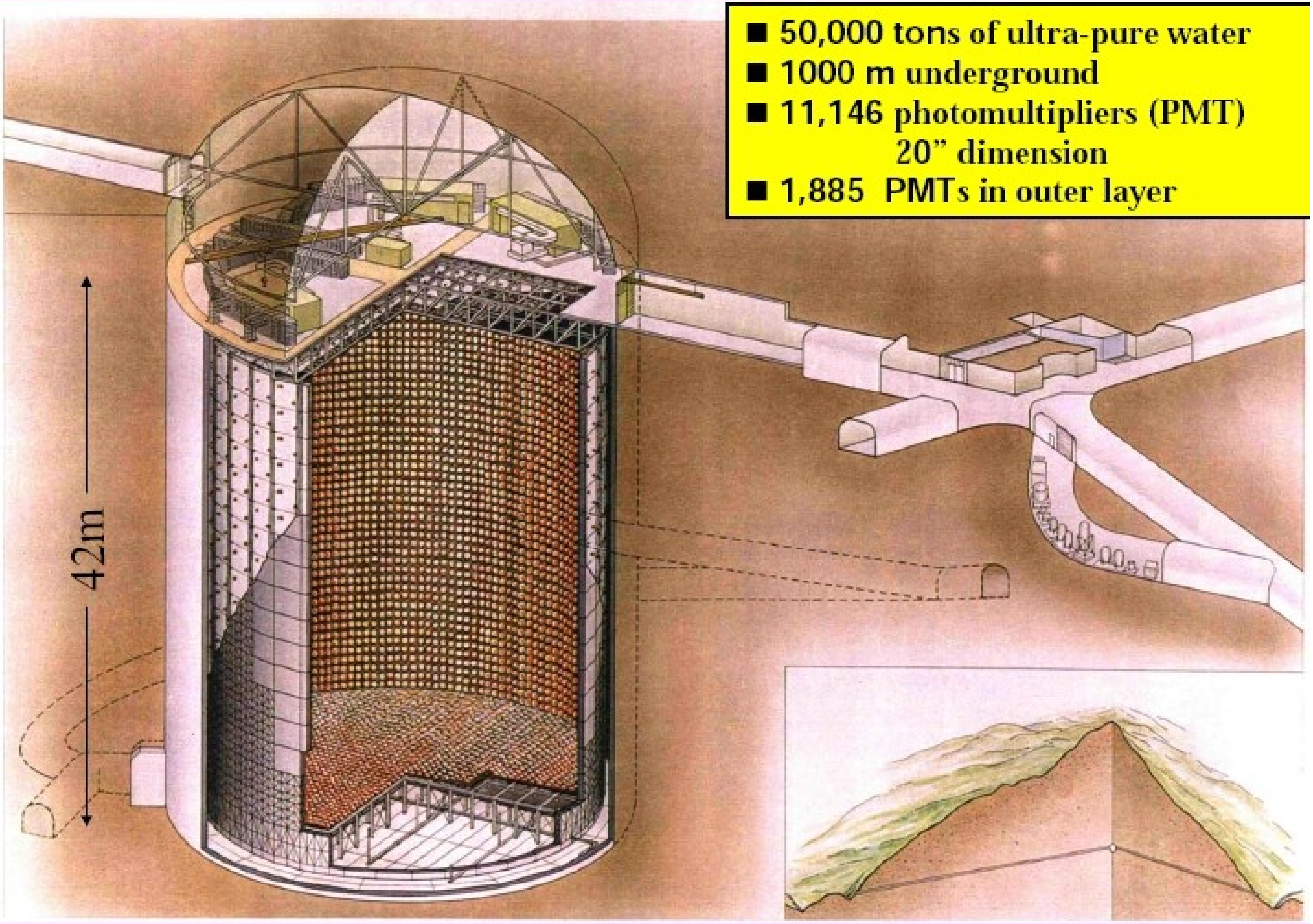
The shockwave can be detected and used to measure the particle direction and vertex.
Particles below threshold and neutral particles are not detected

Principle of operation

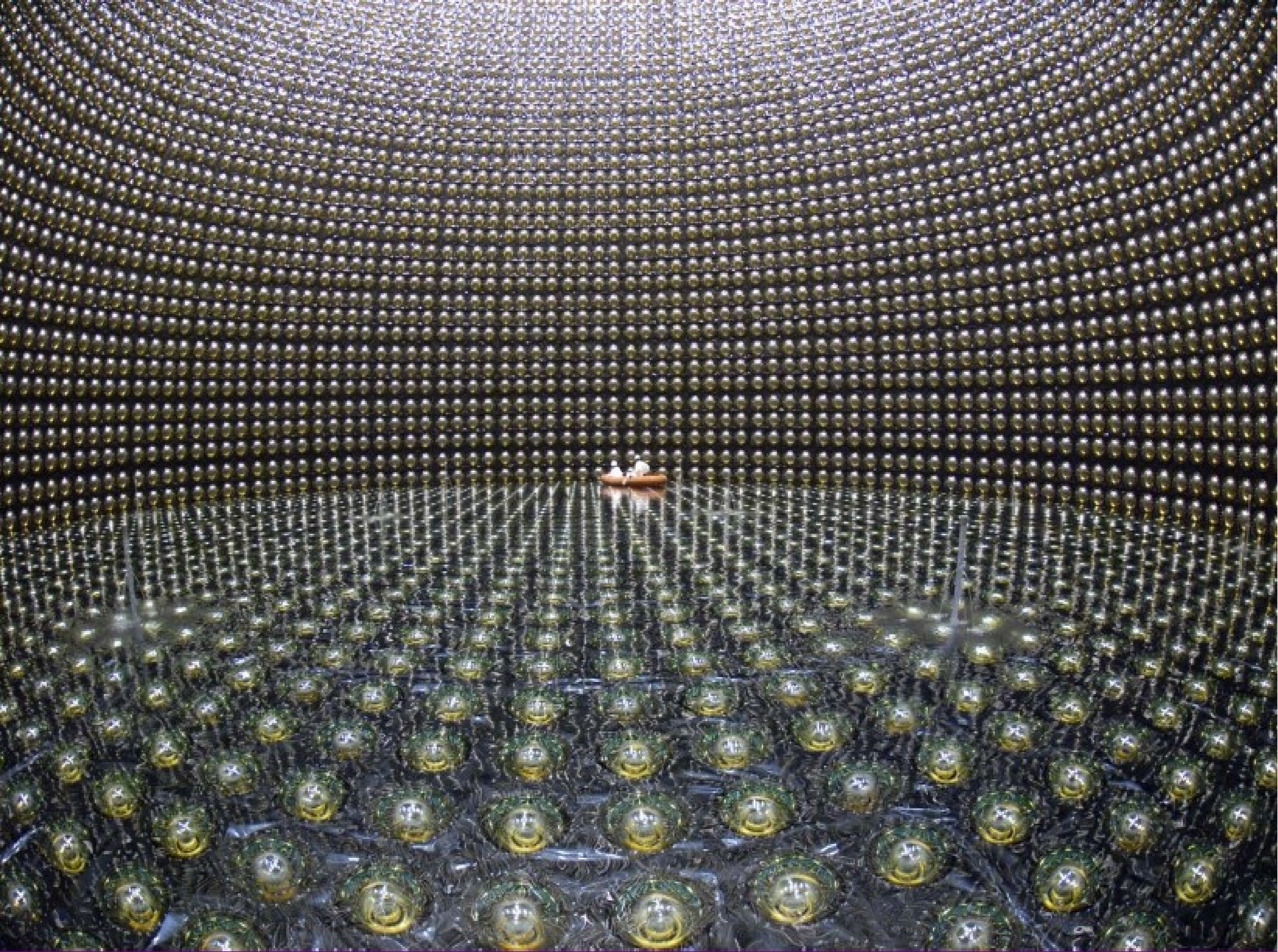


- Cerenkov light detected as a ring or circle by PMTs
- Vertex from timing
- Direction from cone
- Energy from summed light
- No neutrals or charged particles under Cerenkov threshold
- Low multiplicity events

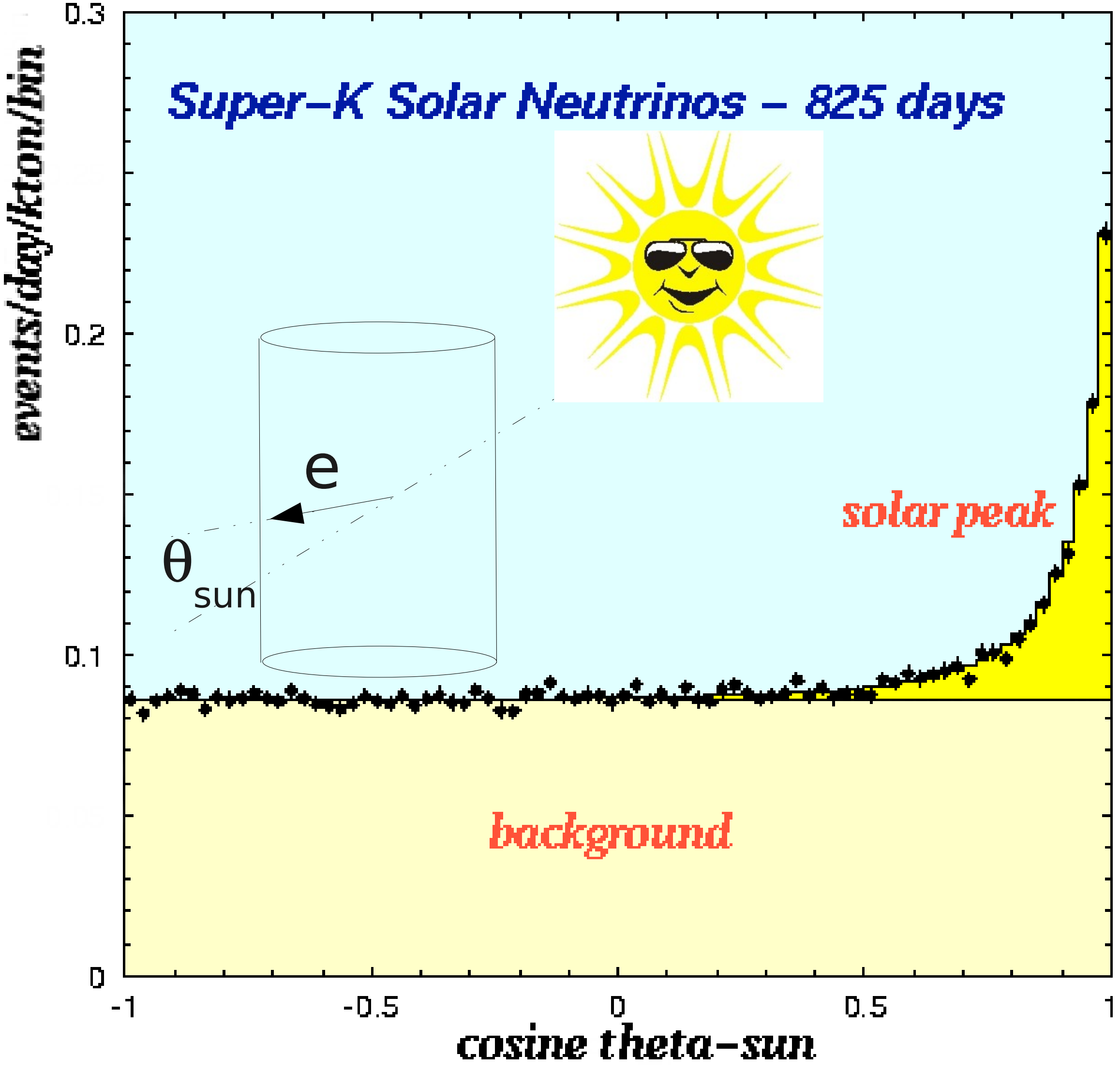
Super-Kamiokande



- 50,000 tons of ultra-pure water
- 1000 m underground
- 11,146 photomultipliers (PMT) 20" dimension
- 1,885 PMTs in outer layer

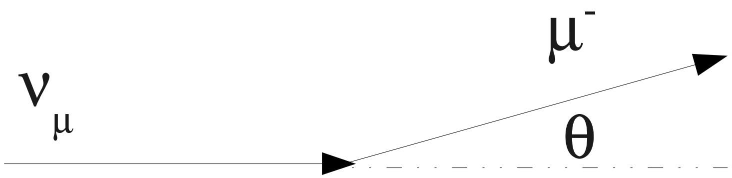


Directionality

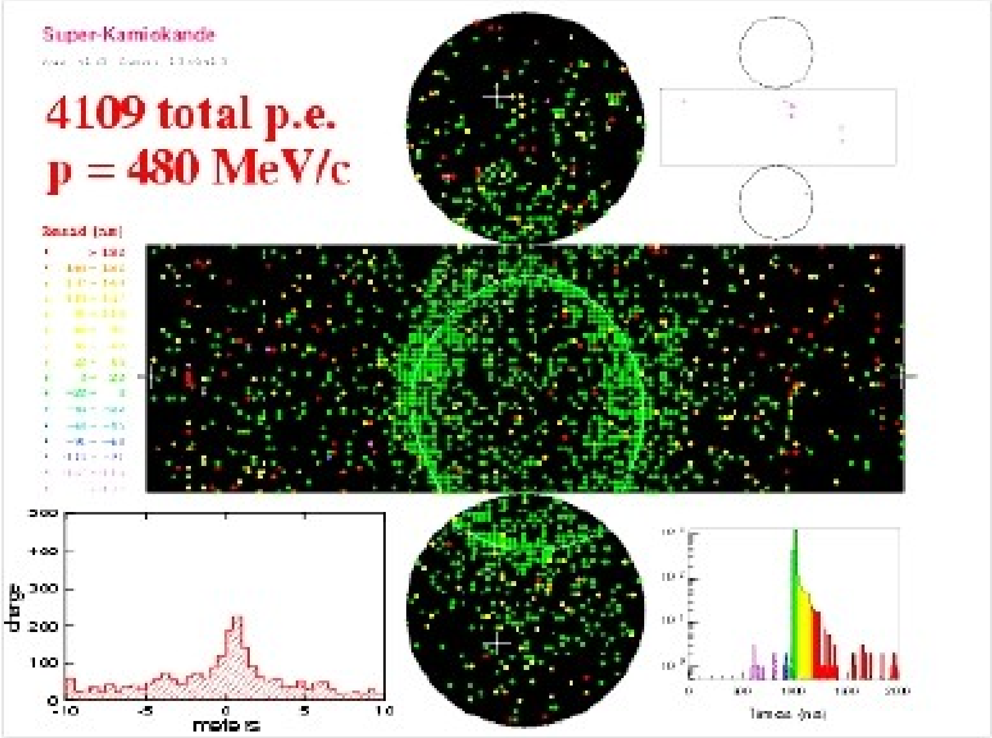


For simple events , the direction of the ring can be used to point back to the neutrino source

Proof that these neutrinos were coming from the sun



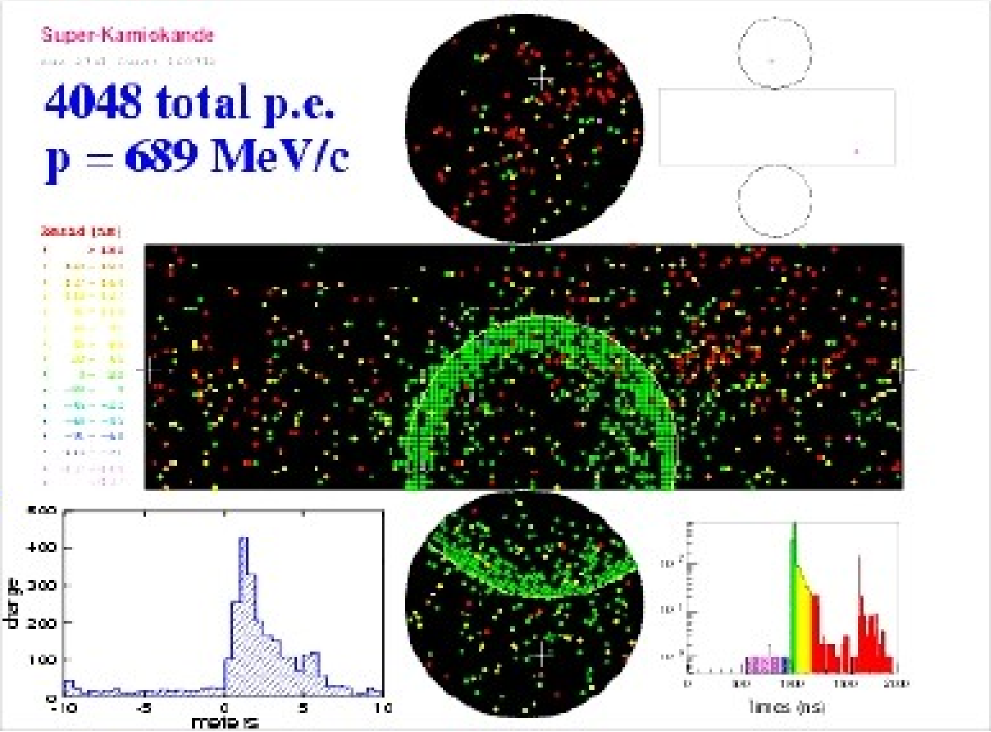
e–like



Colours = time of hit
Event energy = sum of PMT signals

Electron-like : has a fuzzy ring

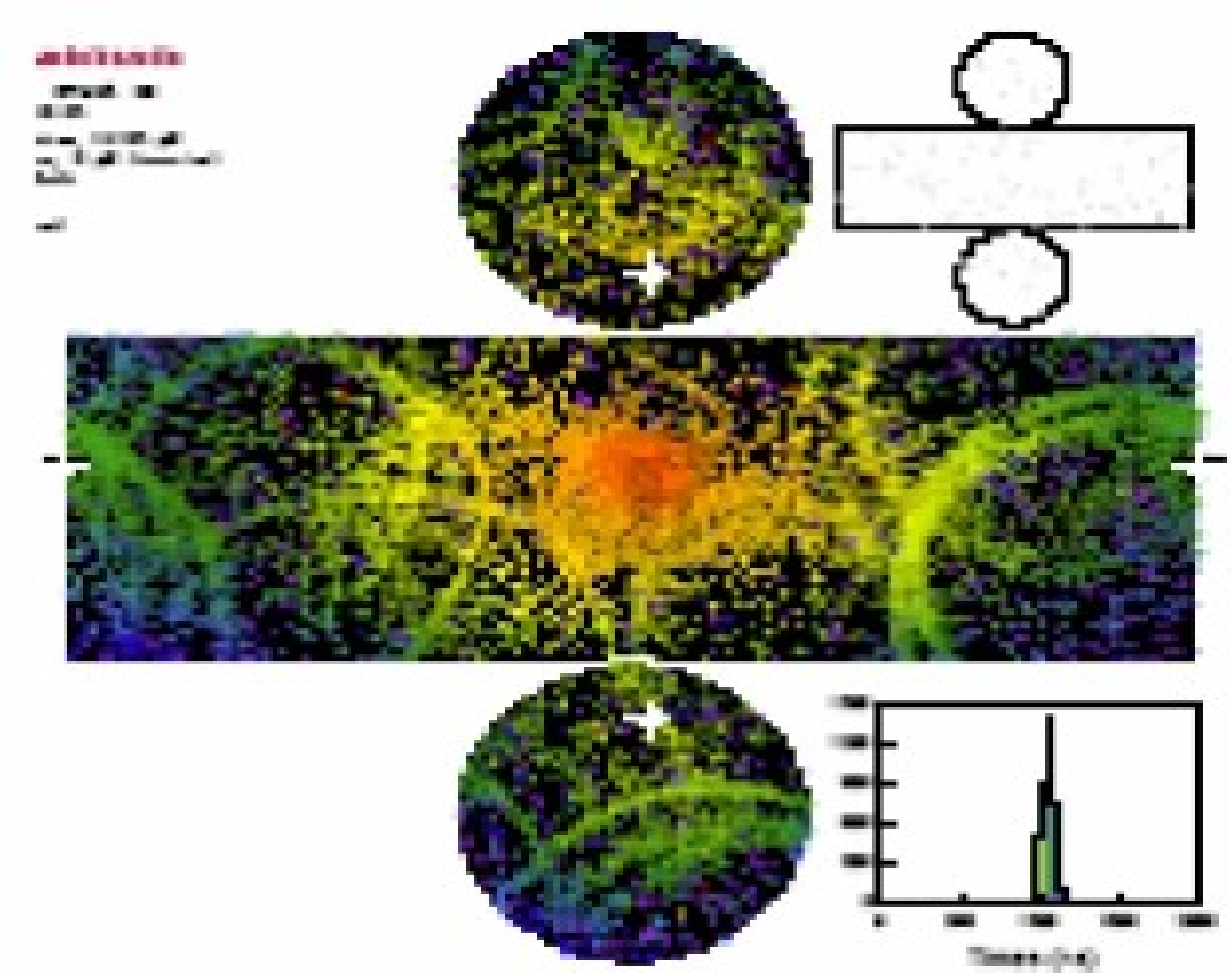
μ–like



Muon-like : has a sharp edged ring and particle stopped in detector.

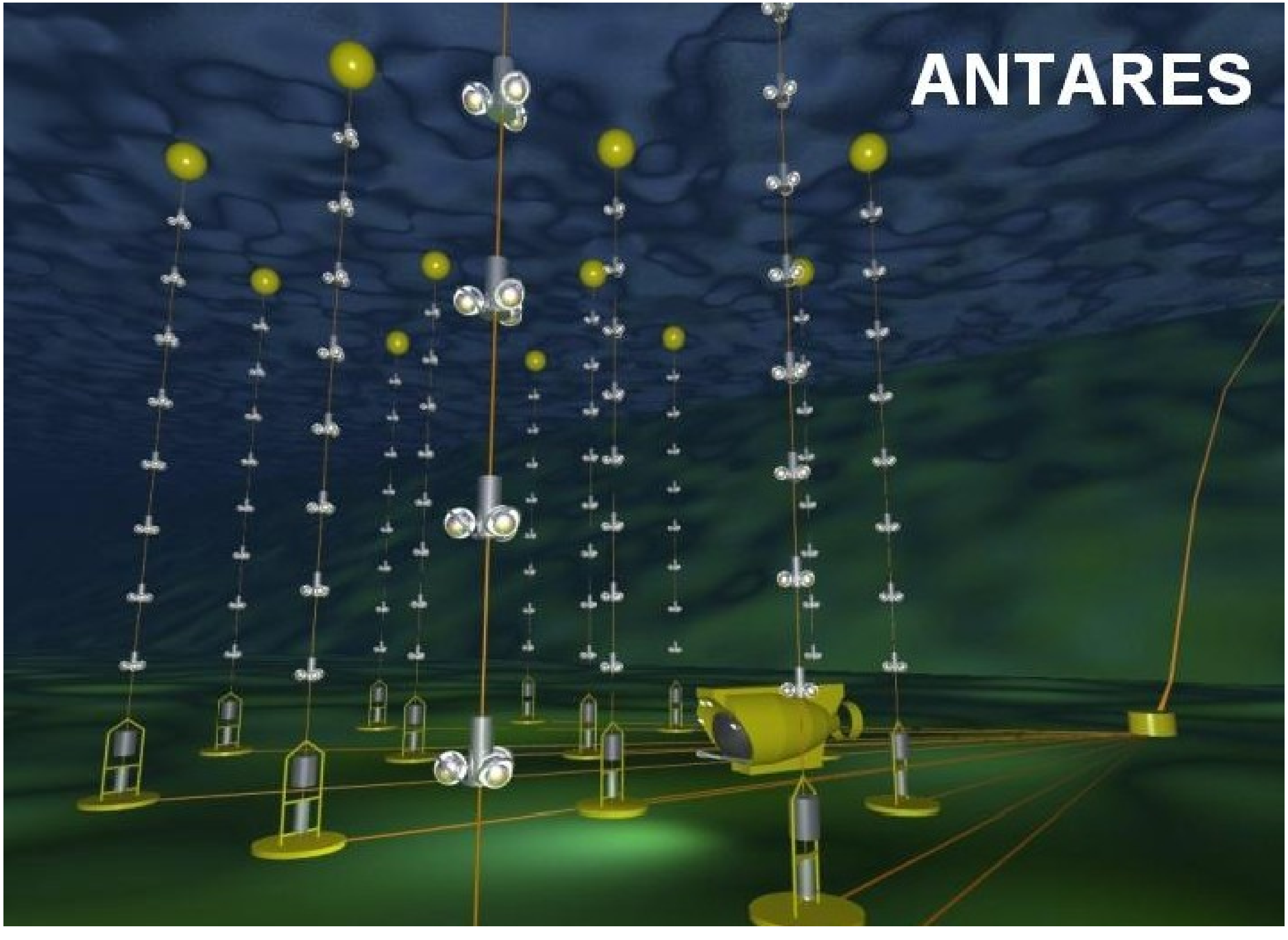
Problems

- Any particle below threshold is not seen
- Neutral particles are not observed
- Multi-ring events are extremely hard to reconstruct



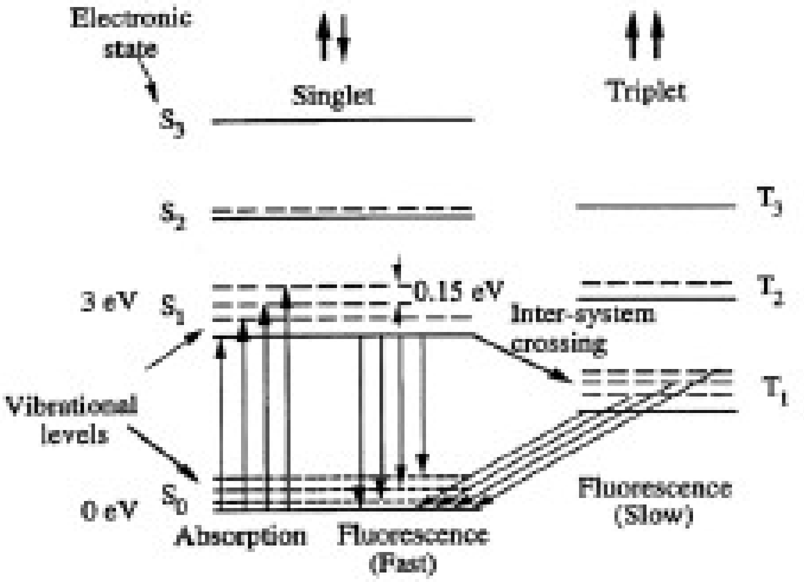
Deep Water Detectors

Sited off Toulon in the Mediterranean @2400m depth



Scintillator Detectors

Emission of a pulse light following ionisation



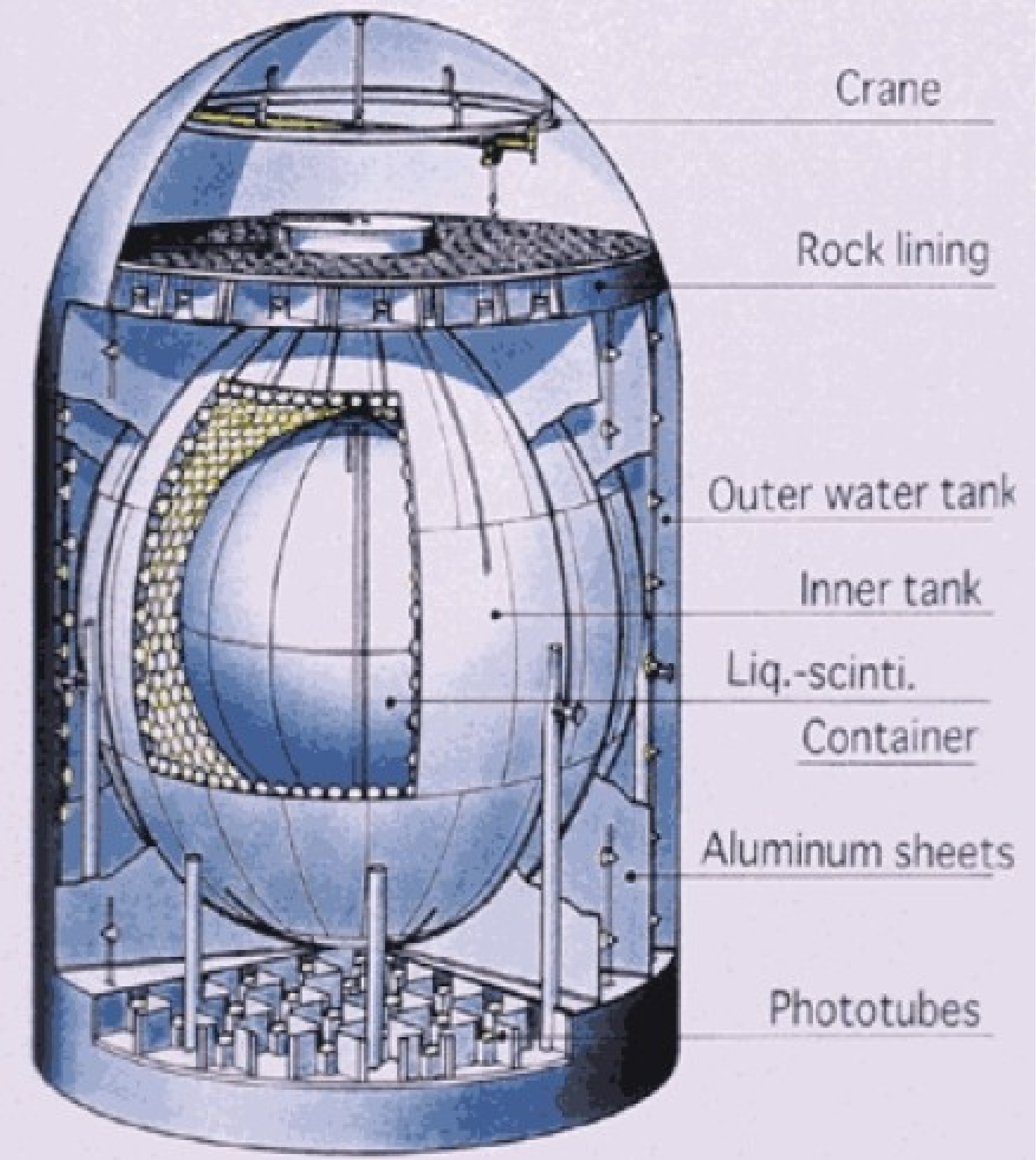
Organic liquids and plastics

Inorganic crystals

Nobel liquids

- In a good scintillator, much more light is emitted by scintillation than by the Cerenkov process.
- Scintillation light is isotropic and there is no threshold.
- But no information on directionality,the emission wavelength depends on the scintillator material, and the scintillator is usually highly toxic.

KamLAND



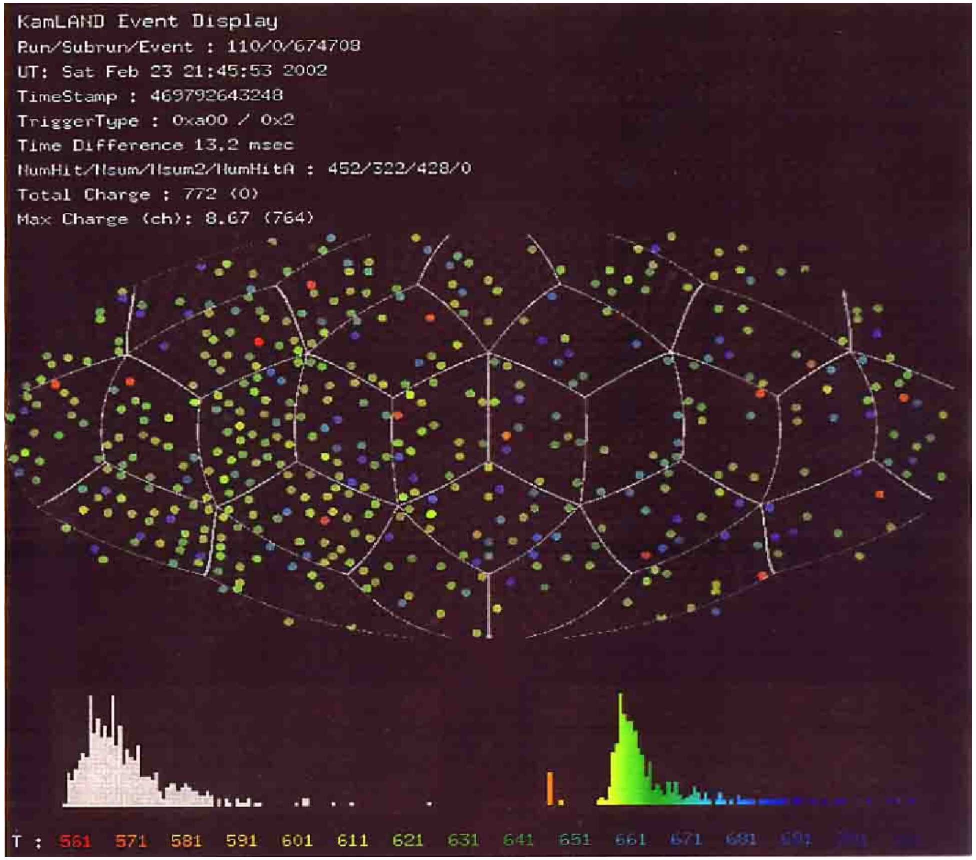
- External container filled with 3.2 kton H_2O
- Inner sphere filled with 2 kton of mineral oil
- Inside transparent balloon filled with 1 kton of liquid scintillator
- Located 1km deep in the Kamioka mine, just up the street from Super-Kamiokande
- Very pure – background is a major problem.

Event Displays

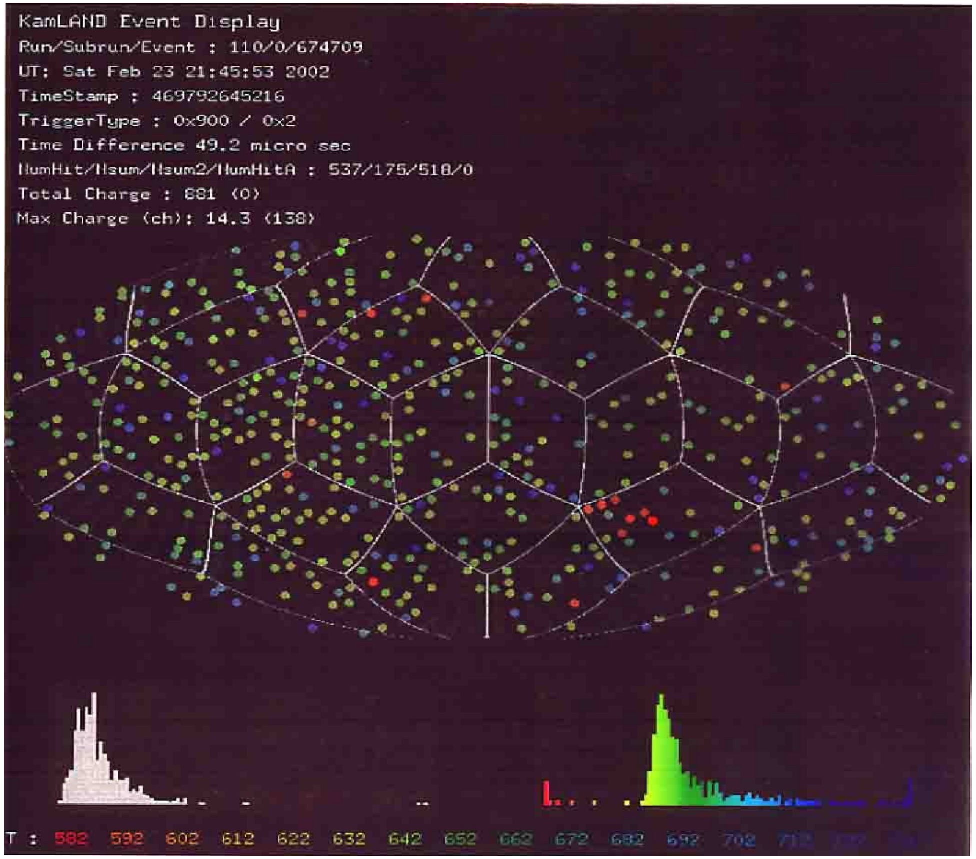
$\overline{\nu}_e + p \rightarrow e^+ + n$

200 ms later

$n + p \rightarrow d + \gamma$



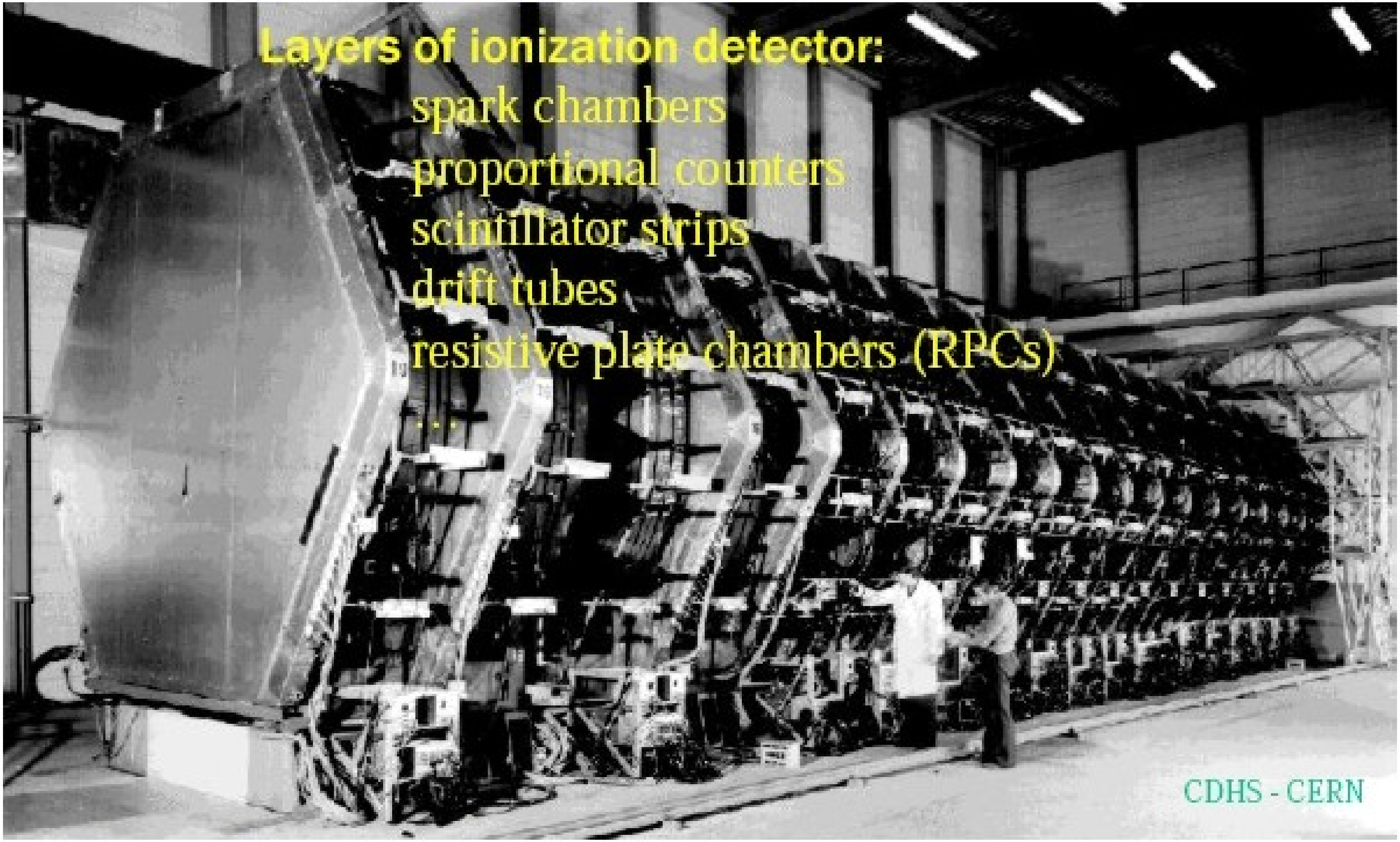
```
KamLAND Event Display
Run/Subrun/Event : 110/0/674708
UT: Sat Feb 23 21:45:53 2002
TimeStamp : 469792643248
TriggerType : 0xa00 / 0x2
Time Difference 13.2 msec
NumHit/Nsum/Nsum2/NumHitA : 452/322/428/0
Total Charge : 772 (0)
Max Charge (ch): 8.67 (764)
```



```
KamLAND Event Display
Run/Subrun/Event : 110/0/674709
UT: Sat Feb 23 21:45:53 2002
TimeStamp : 469792645216
TriggerType : 0x900 / 0x2
Time Difference 49.2 micro sec
NumHit/Nsum/Nsum2/NumHitA : 537/175/518/0
Total Charge : 881 (0)
Max Charge (ch): 14.3 (138)
```

Tracking Calorimeters

Layers of target: eg. steel, marble, glass



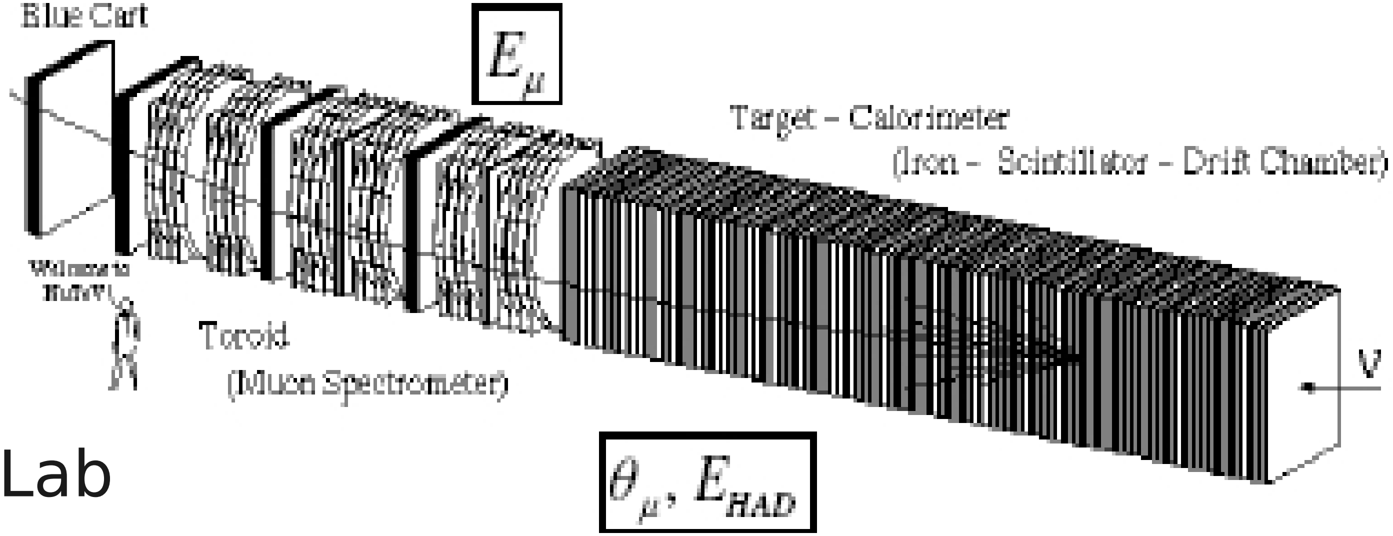
Layers of ionization detector:

- spark chambers
- proportional counters
- scintillator strips
- drift tubes
- resistive plate chambers (RPCs)
- ...

CDHS - CERN

NuTeV

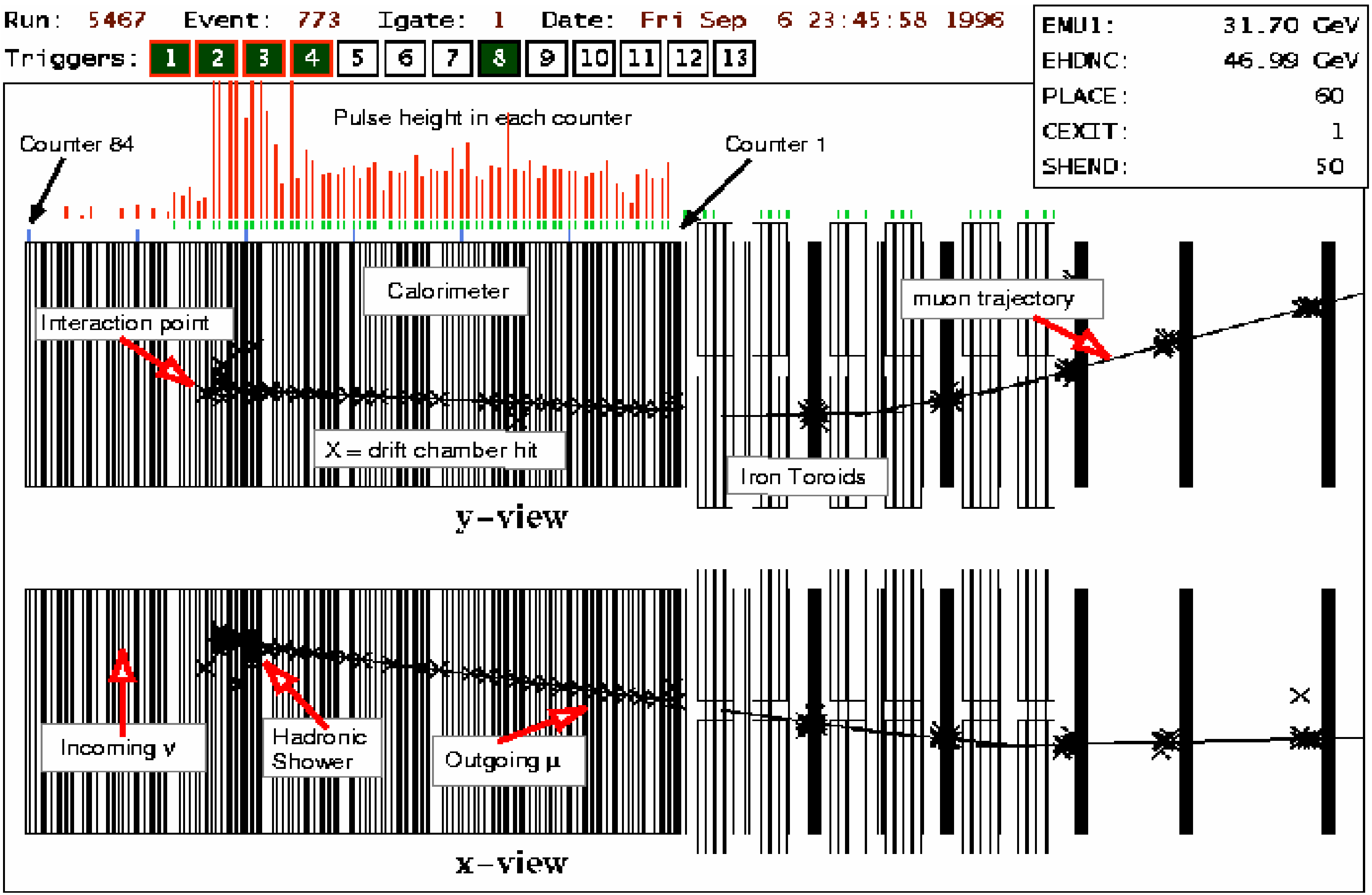
Iron Sampling calorimeter : CDHS,CHARM,CCFR,NUTEV,MINOS



FermiLab

- Typically used for high energy (> a few GeV) beams
- Iron plates (target) interspersed by scintillator planes
- Muon tracked and radius of curvature measured in toroid
- Hadronic energy summed from active detector but single track resolution is not achievable

NuTeV

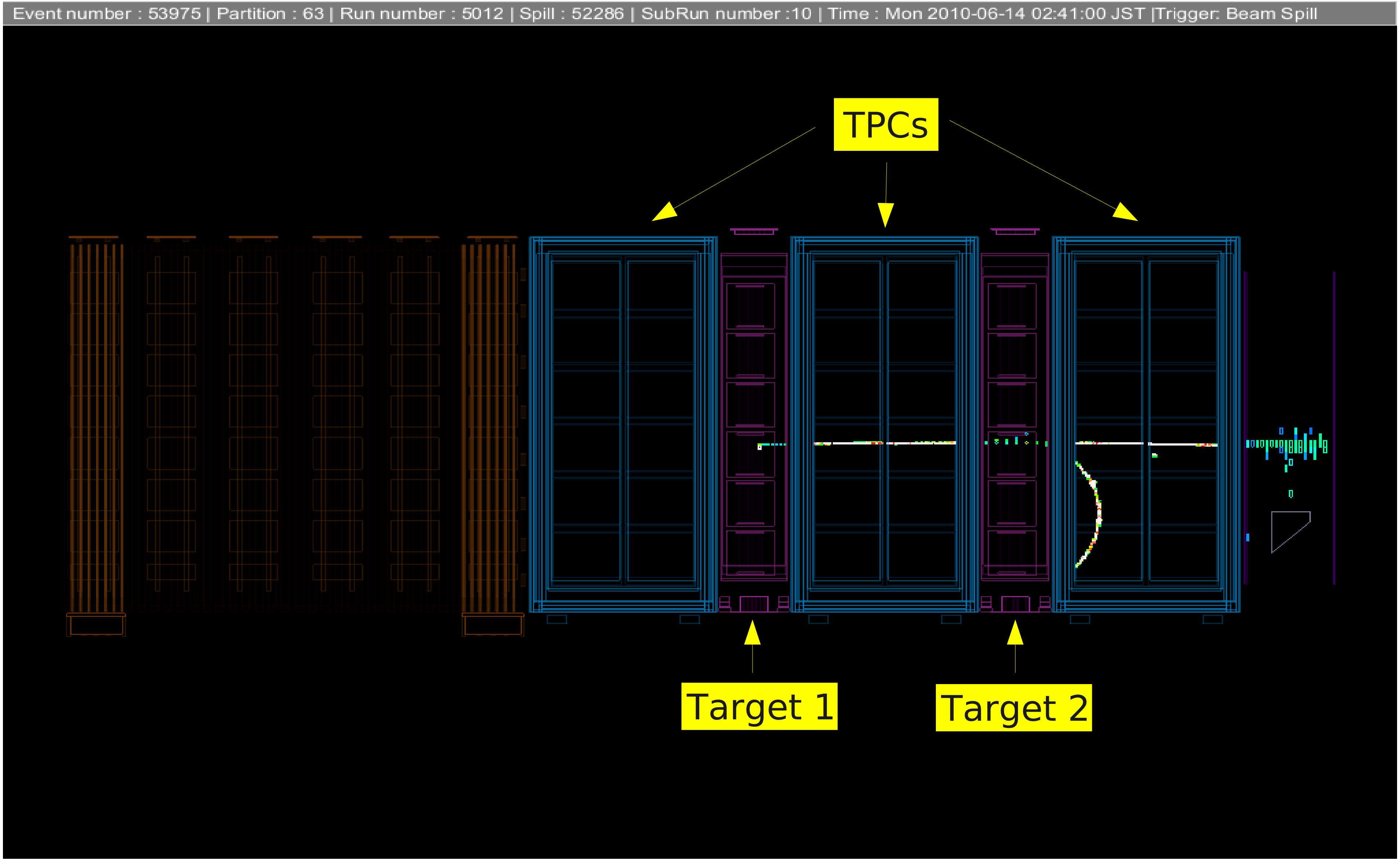


Run: 5467 Event: 773 Igate: 1 Date: Fri Sep 6 23:45:58 1996

Triggers: 1 2 3 4 5 6 7 8 9 10 11 12 13

EMU1:	31.70 GeV
EHDNC:	46.99 GeV
PLACE:	60
CEXIT:	1
SHEND:	50

T2K



Event number : 53975 | Partition : 63 | Run number : 5012 | Spill : 52286 | SubRun number :10 | Time : Mon 2010-06-14 02:41:00 JST |Trigger: Beam Spill

Summary

- Type of neutrino detectors depend on target, event rate, and interaction type and cost
- 4 “main” techniques
  - radiochemical (low threshold but no direction or timing information - sub-MeV neutrinos)
  - water cerenkov (high threshold, cheap target mass, direction and timing but only low multiplicity events - 100 MeV up to a few GeV)
  - scintillator (no threshold but no directionality unless enhanced by water cerenkov - few MeV)
  - tracking calorimeters (high energy events - full reconstruction of events - 1 GeV and up)