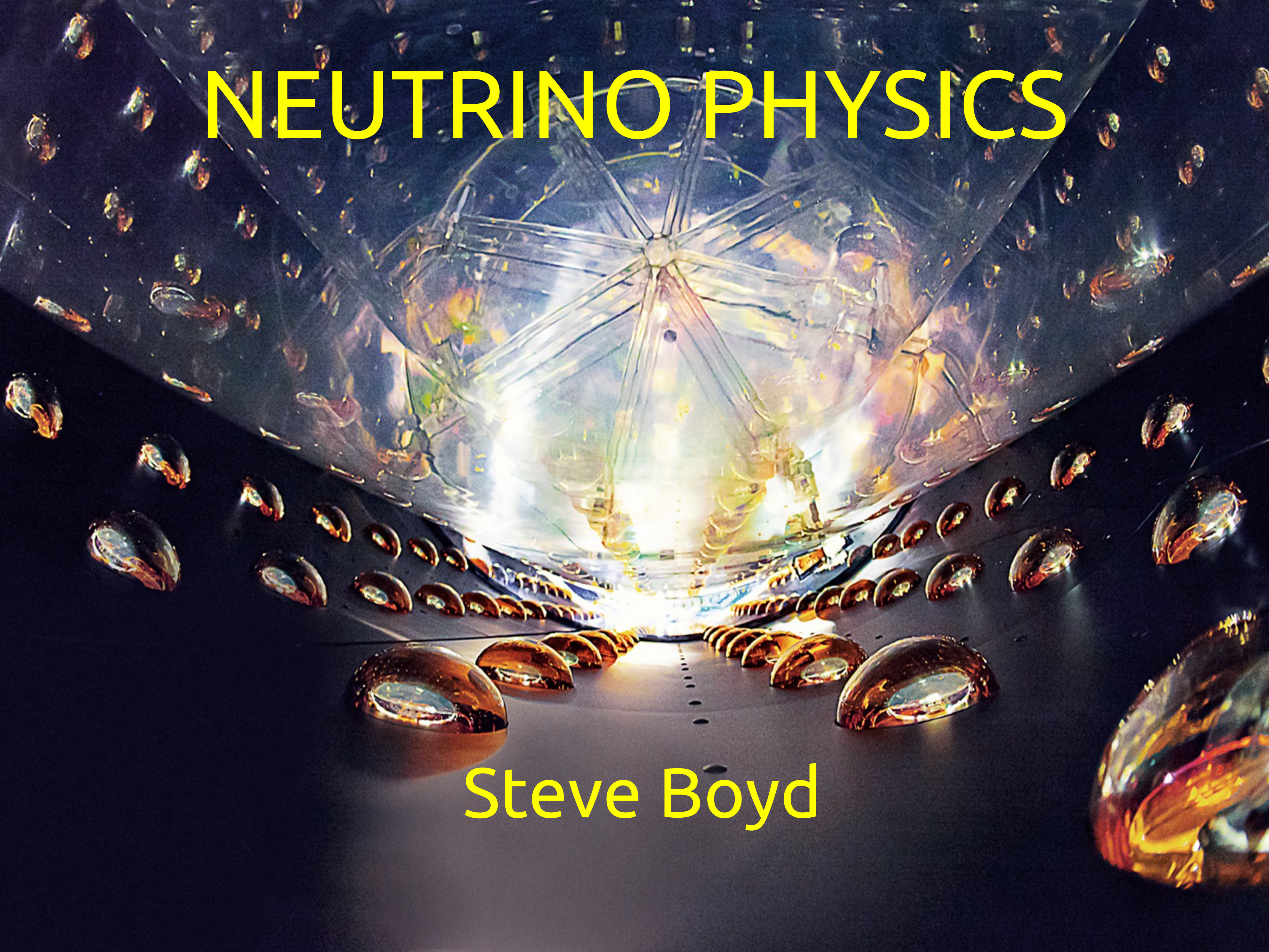


NEUTRINO PHYSICS

Steve Boyd

What's in the lectures

1. History and properties of the neutrino, neutrino interactions, beams and detectors
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

Lecture 1

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

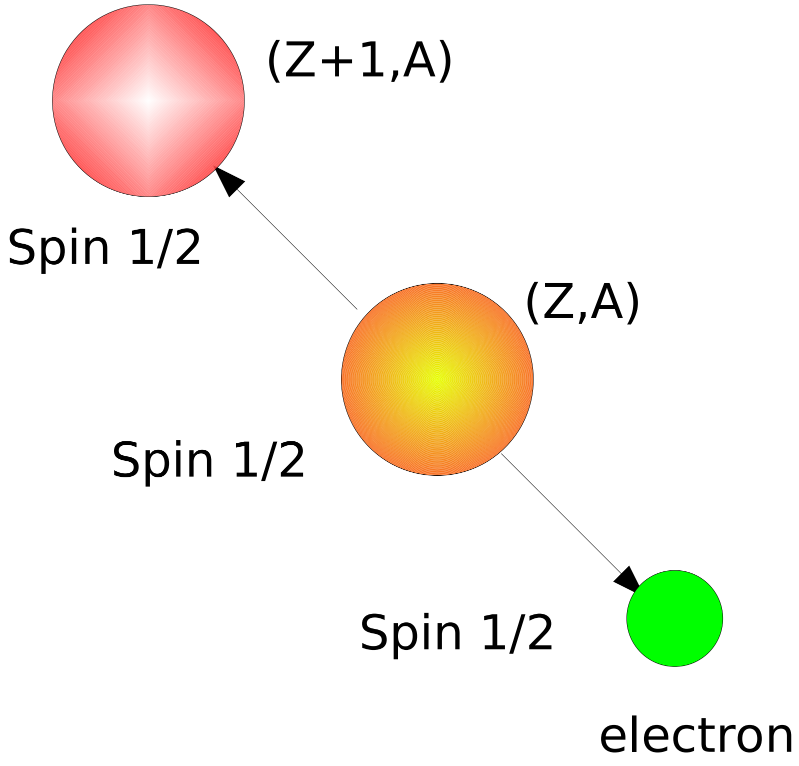
An Ode to Neutrinos

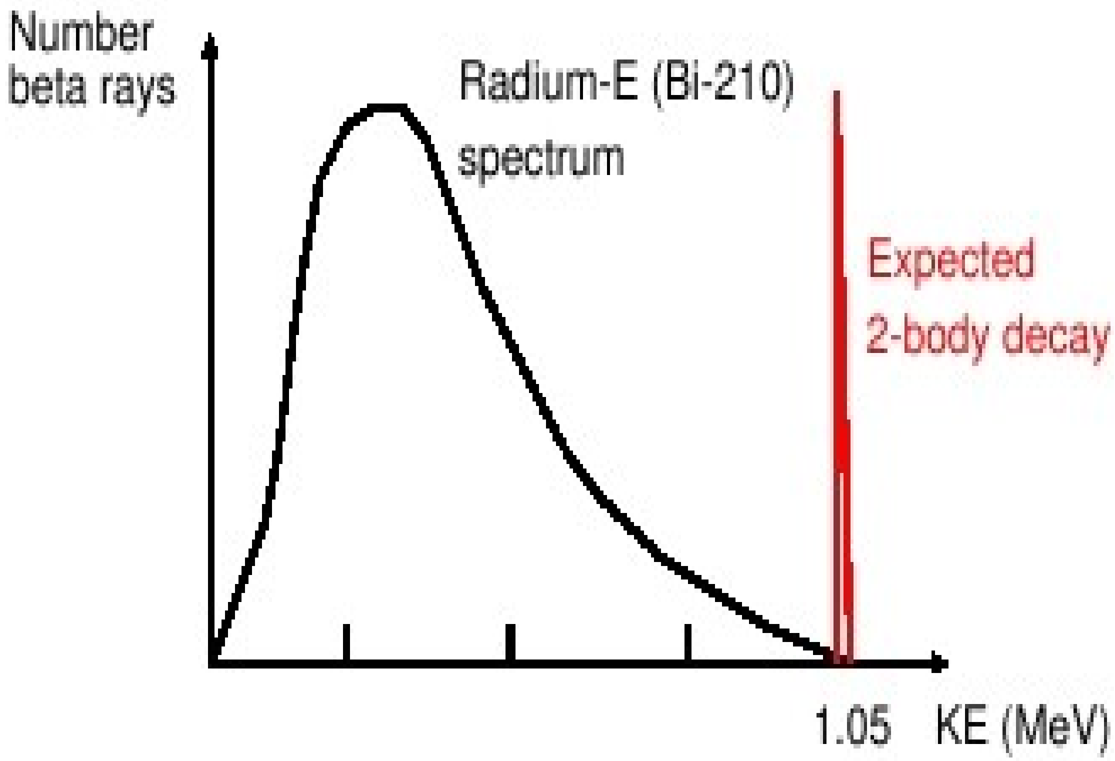
Neutrinos they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a dusty hall….

”Cosmic gall”,
John Updike,
Telephone Poles and other Poems,
1963

Crisis

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





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”

4th December 1930
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 beta spectrum, I have hit upon a desperate remedy to save the ”exchange theorem” 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 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 beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...*

From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately I will not be able to appear in Tubingen personally, because I am indispensible here due to a ball which will take place in Zurich during the night from December 6 to 7...

Your humble servant,
W. Pauli

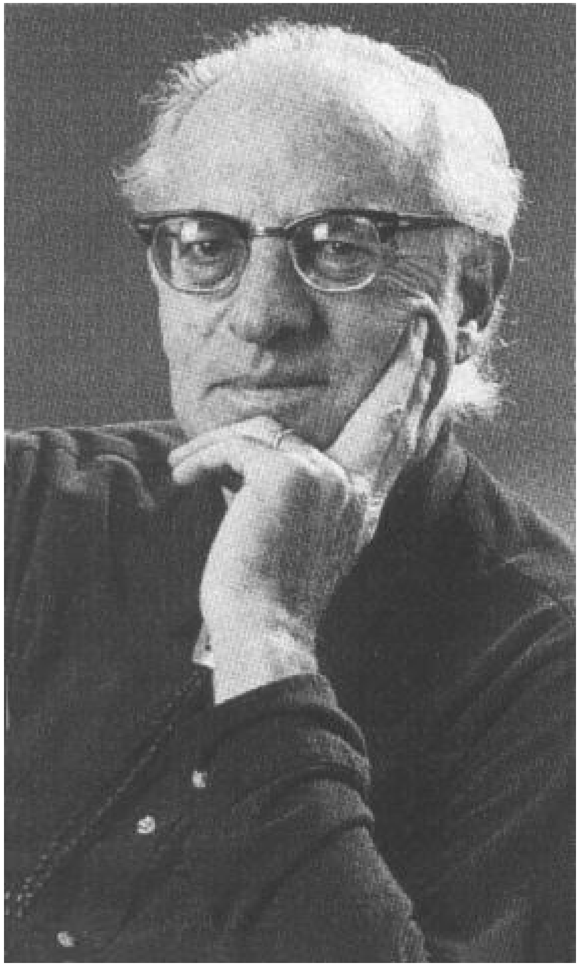
Oh the pain

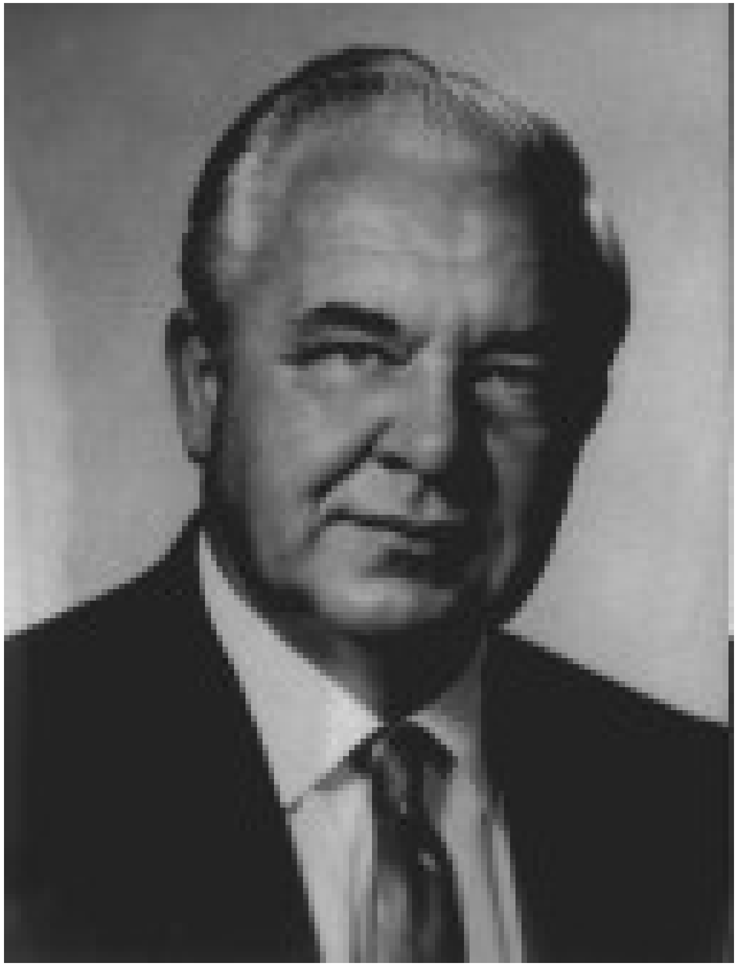
“I have done something very bad today by proposing a particle that cannot be detected. It is something that no theorist should ever do.”

Pauli, 1930

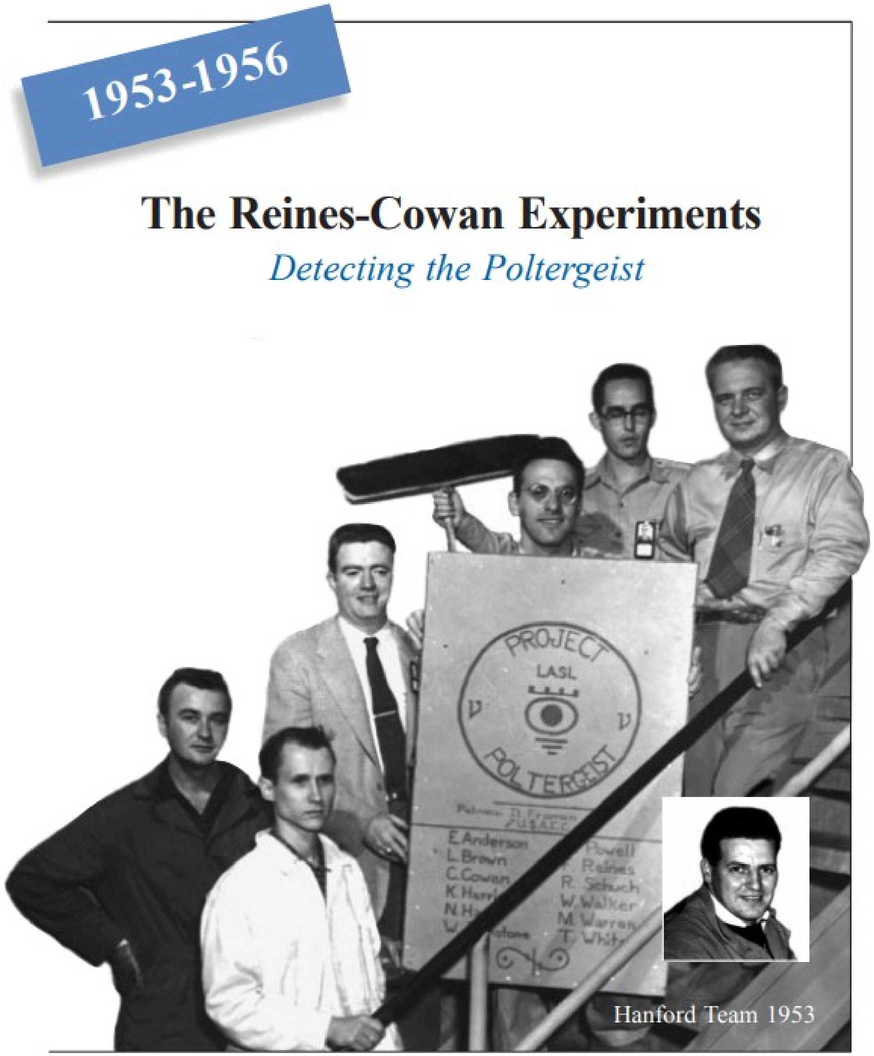
Detection of the Neutrino

1950 – Reines and Cowan set out to detect ν





Detection of the Neutrino

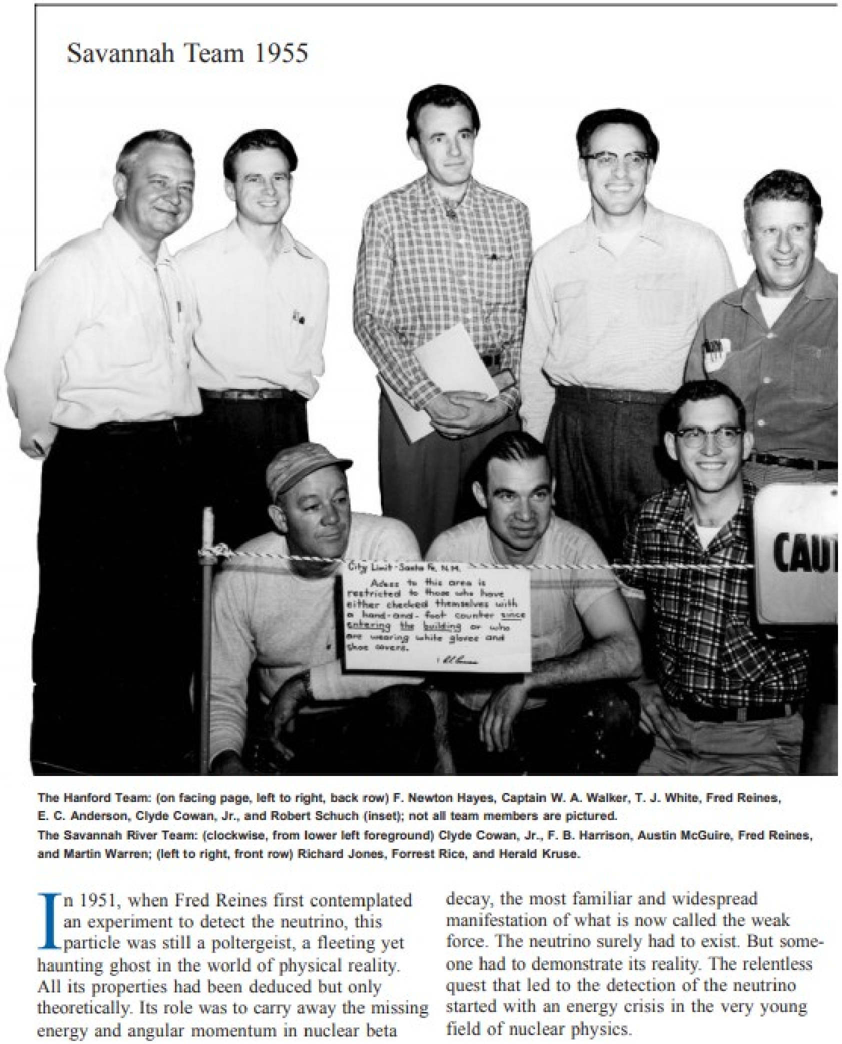


1953-1956

The Reines-Cowan Experiments

Detecting the Poltergeist

Hanford Team 1953

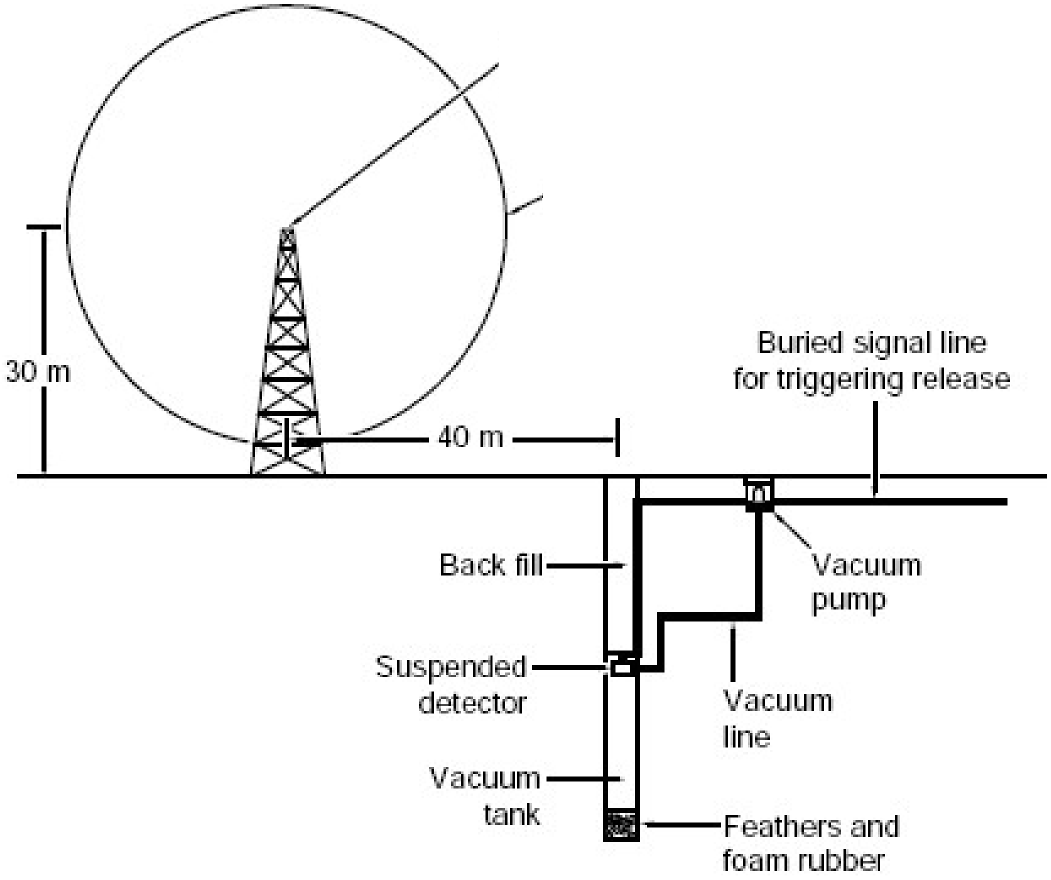


Savannah Team 1955

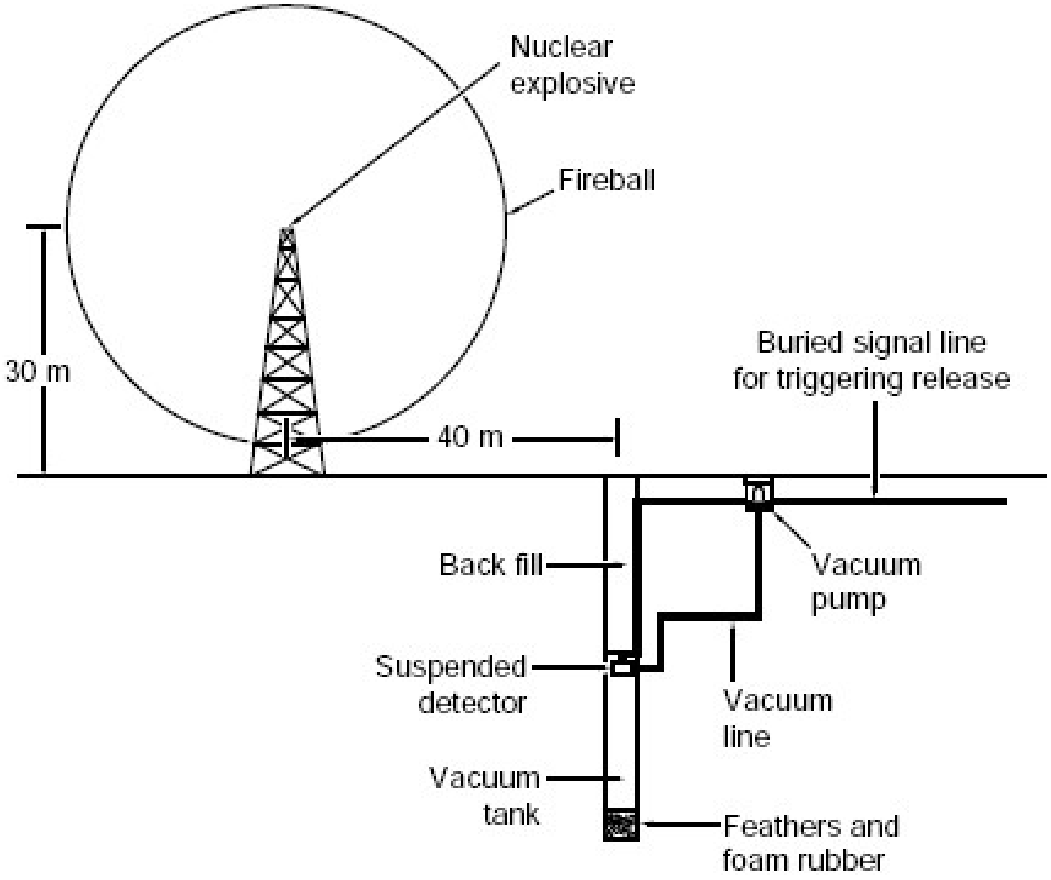
The Hanford Team: (on facing page, left to right, back row) F. Newton Hayes, Captain W. A. Walker, T. J. White, Fred Reines, E. C. Anderson, Clyde Cowan, Jr., and Robert Schuch (inset); not all team members are pictured.
The Savannah River Team: (clockwise, from lower left foreground) Clyde Cowan, Jr., F. B. Harrison, Austin McGuire, Fred Reines, and Martin Warren; (left to right, front row) Richard Jones, Forrest Rice, and Herald Kruse.

In 1951, when Fred Reines first contemplated an experiment to detect the neutrino, this particle was still a poltergeist, a fleeting yet haunting ghost in the world of physical reality. All its properties had been deduced but only theoretically. Its role was to carry away the missing energy and angular momentum in nuclear beta decay, the most familiar and widespread manifestation of what is now called the weak force. The neutrino surely had to exist. But someone had to demonstrate its reality. The relentless quest that led to the detection of the neutrino started with an energy crisis in the very young field of nuclear physics.

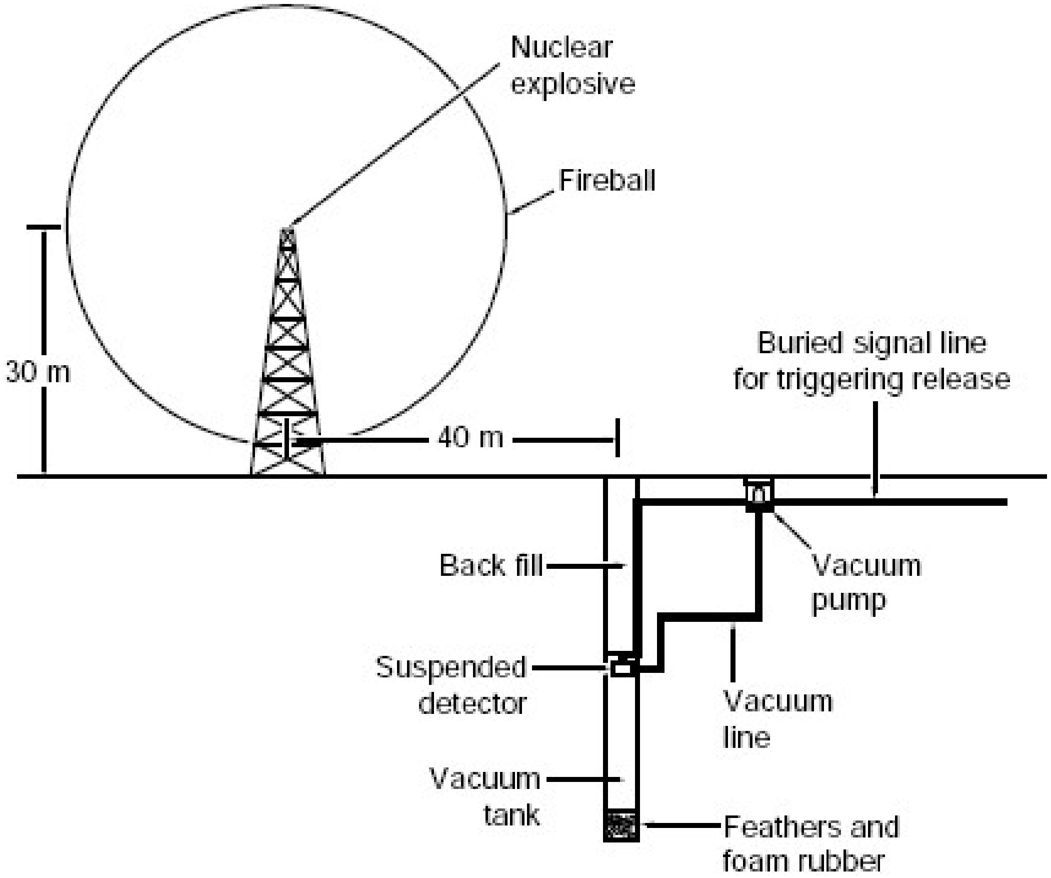
1951


Buried signal line
for triggering release
30 m
40 m
Back fill
Vacuum
pump
Suspended
detector
Vacuum
line
Vacuum
tank
Feathers and
foam rubber

1951


Nuclear explosive
Fireball
30 m
40 m
Buried signal line for triggering release
Back fill
Vacuum pump
Suspended detector
Vacuum line
Vacuum tank
Feathers and foam rubber

1951



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

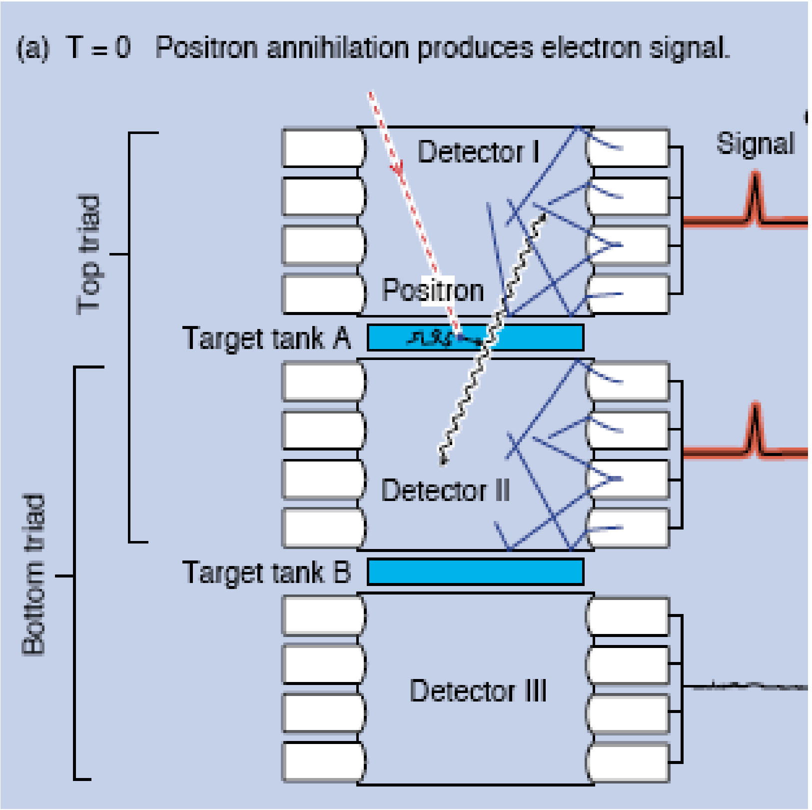
OK – but repeatability is a bit of a problem

Idea Number 2 - 1955

A nuclear reactor is the next best thing

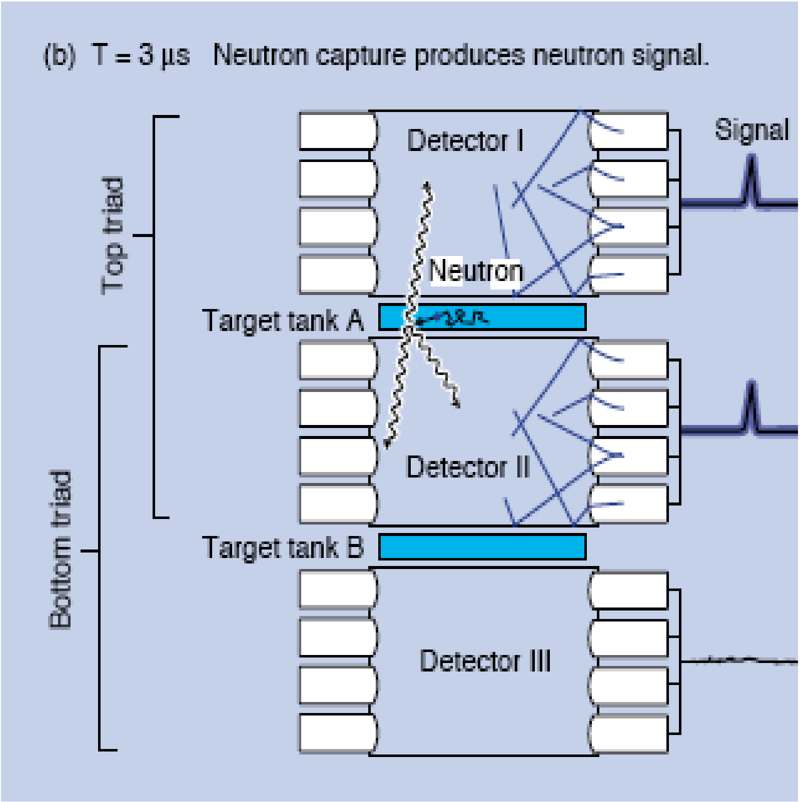
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

Positron Annihilation

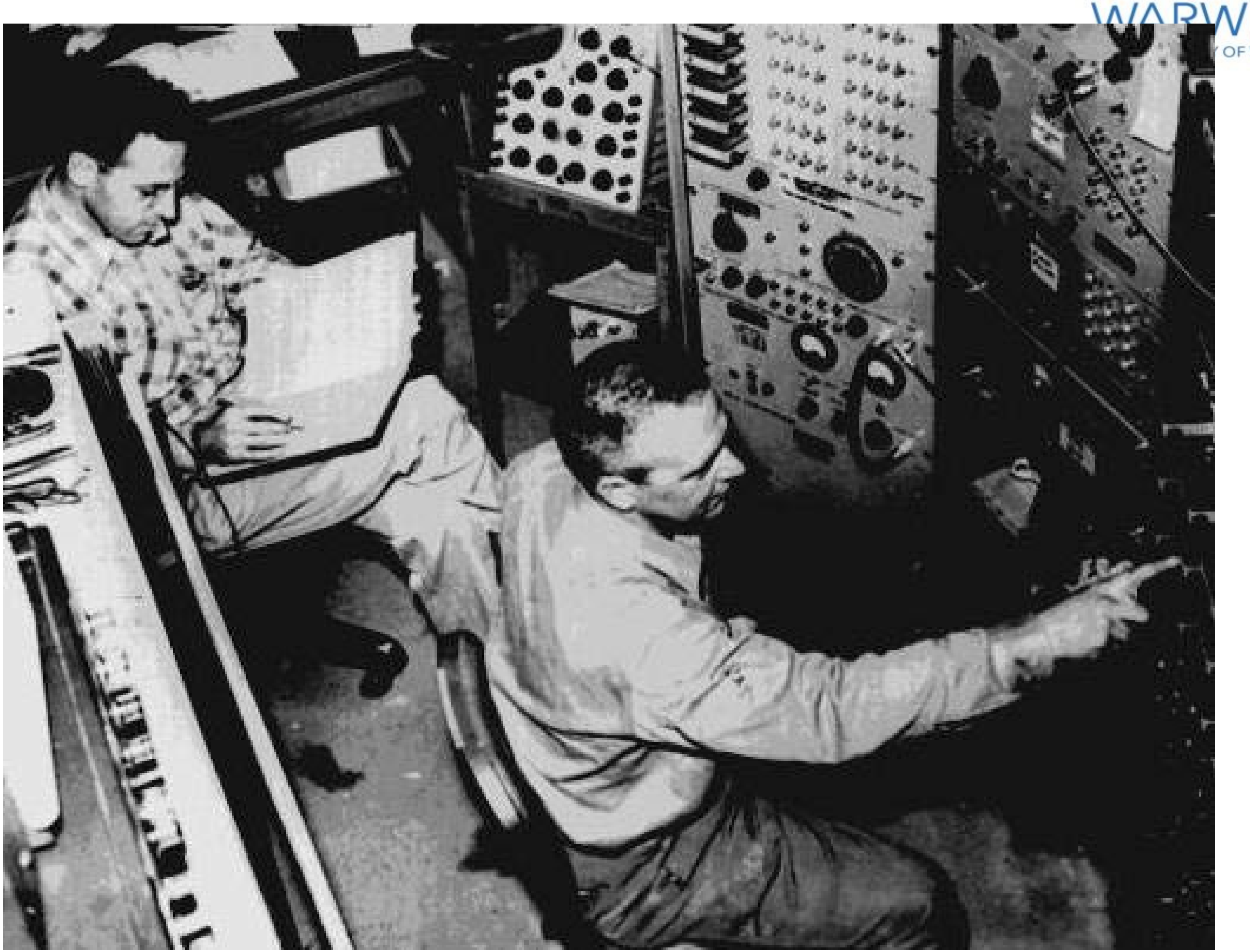


(a) T = 0 Positron annihilation produces electron signal.

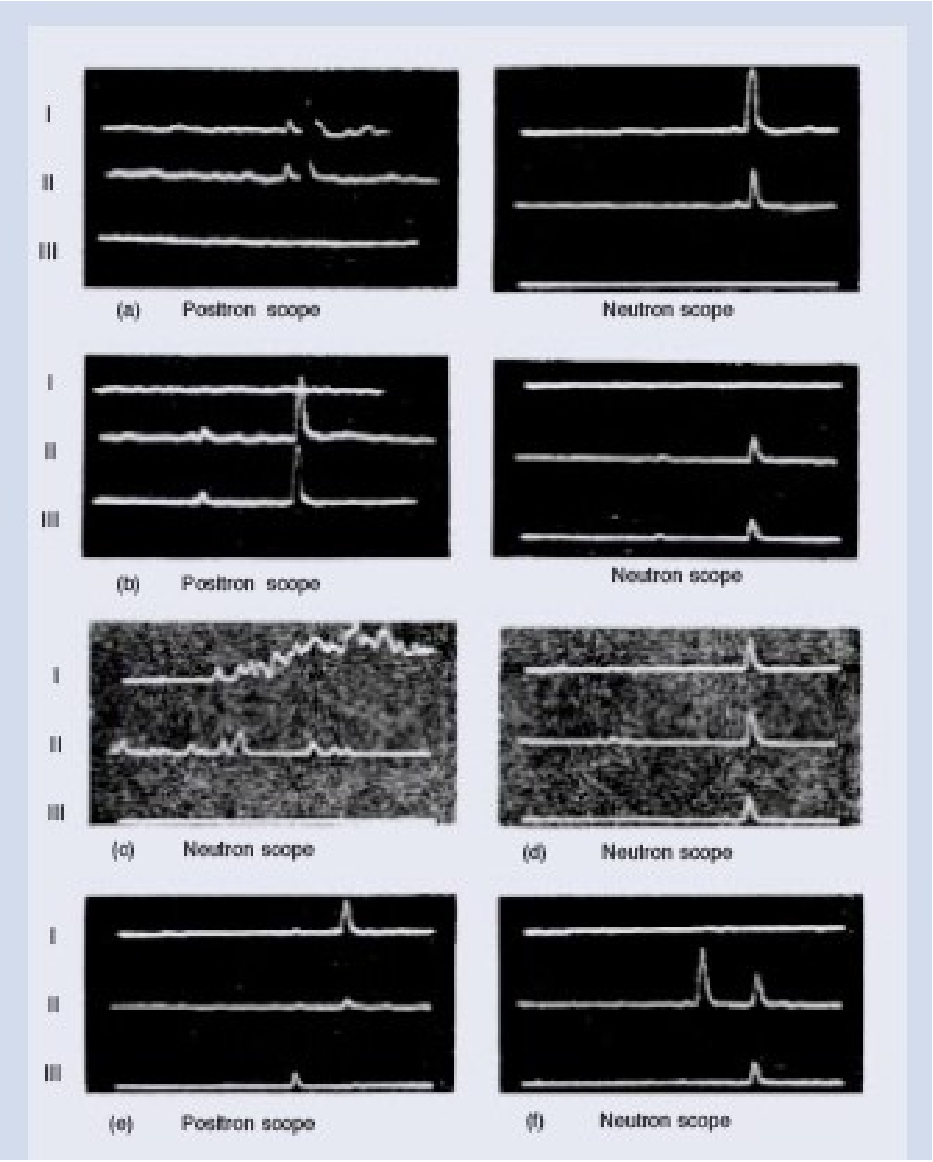
Neutron Capture



(b) T = 3 μs Neutron capture produces neutron signal.



1959 – Savannah River Reactor



$$\text{ON} - \text{OFF} = 2.88 \pm 0.22\ \text{hr}^{-1}$$

$$\sigma = (11 \pm 2.6) \times 10^{-44}\ \text{cm}^2$$

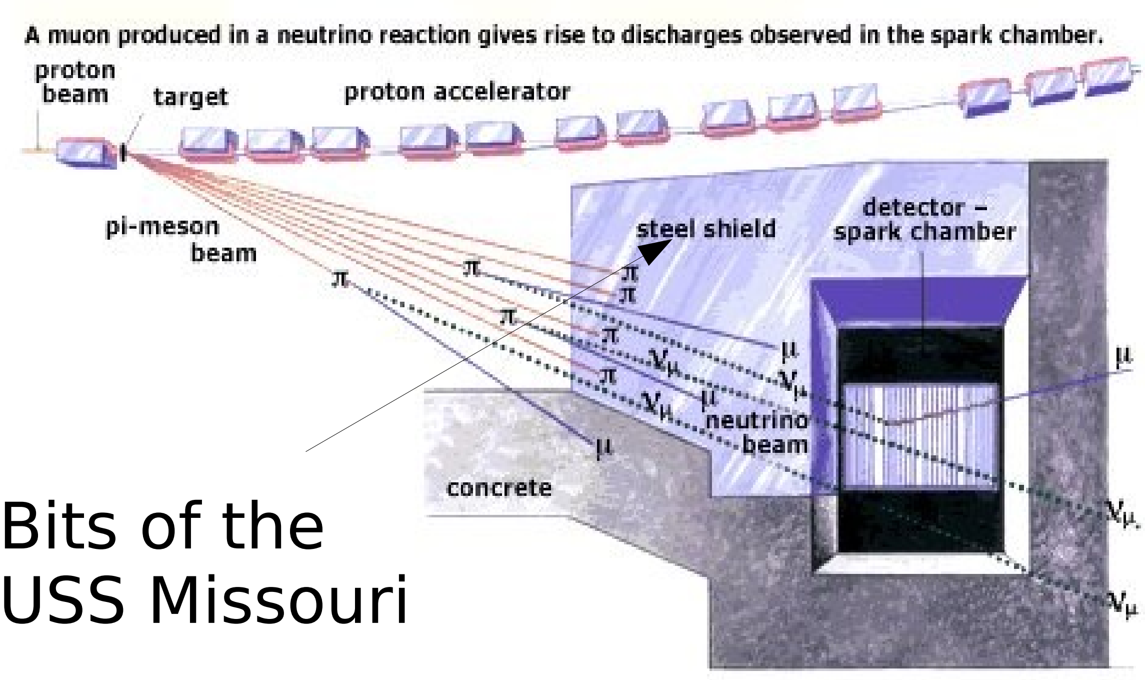
$$\sigma\ (\text{Pred}) = (5 \pm 1) \times 10^{-44}\ \text{cm}^2$$

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

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

$$\nu_\mu + n \rightarrow \mu^- + p$$ OK

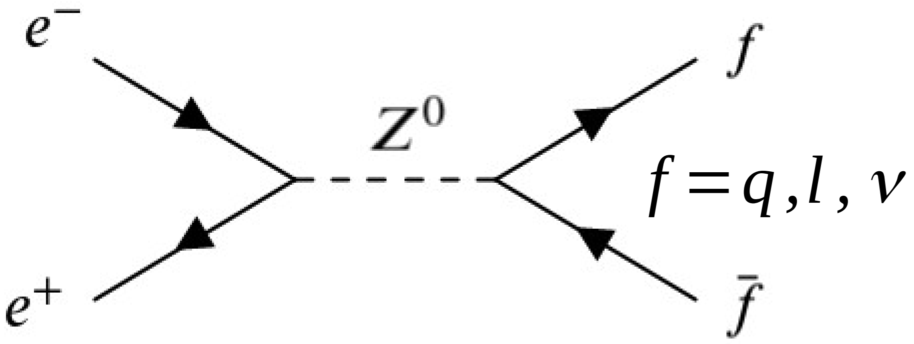
$$\nu_\mu + n \rightarrow e^- + p$$ ~~OK~~

The State of Play pre-2000

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

How many neutrinos do we expect to find?

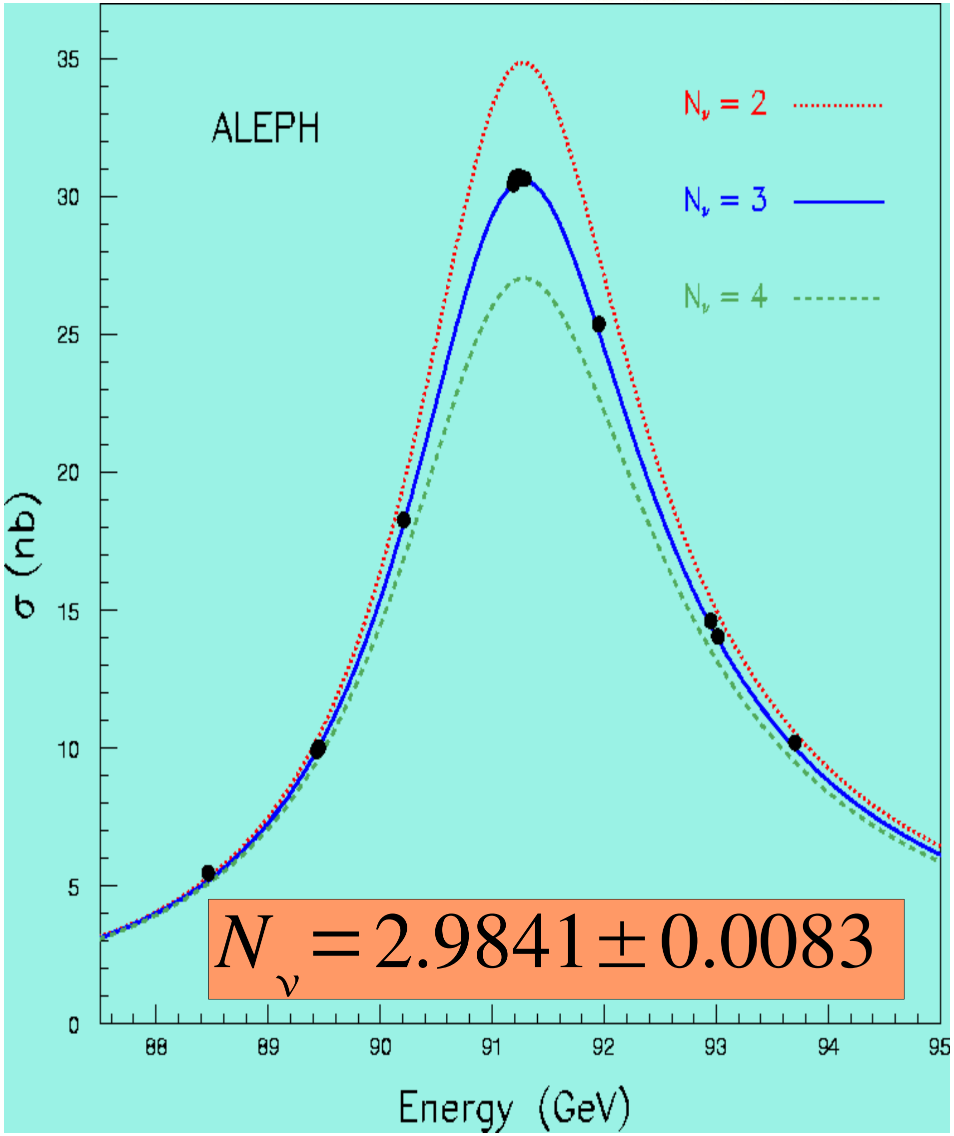
The Number of light neutrinos



$f = q, l, \nu$

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

Discovery of Z^0 allowed a measurement of the number of light neutrinos since the Z^0 can decay to a neutrino and antineutrino



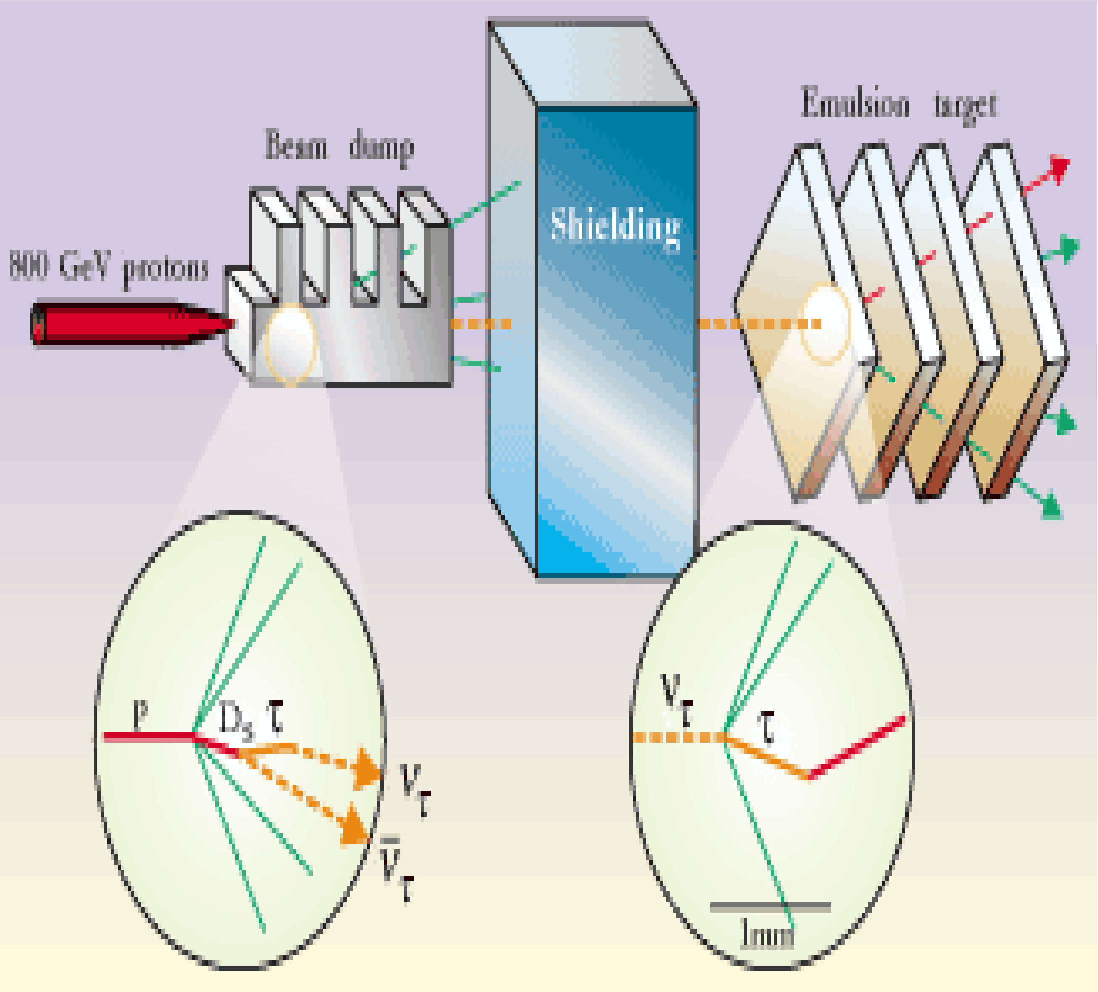
$N_\nu = 2.9841 \pm 0.0083$

NB Mass of $\nu < m_Z/2 \sim 46$ GeV

The Tau Neutrino

ν_τ was finally discovered by DONUT in 2000.

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

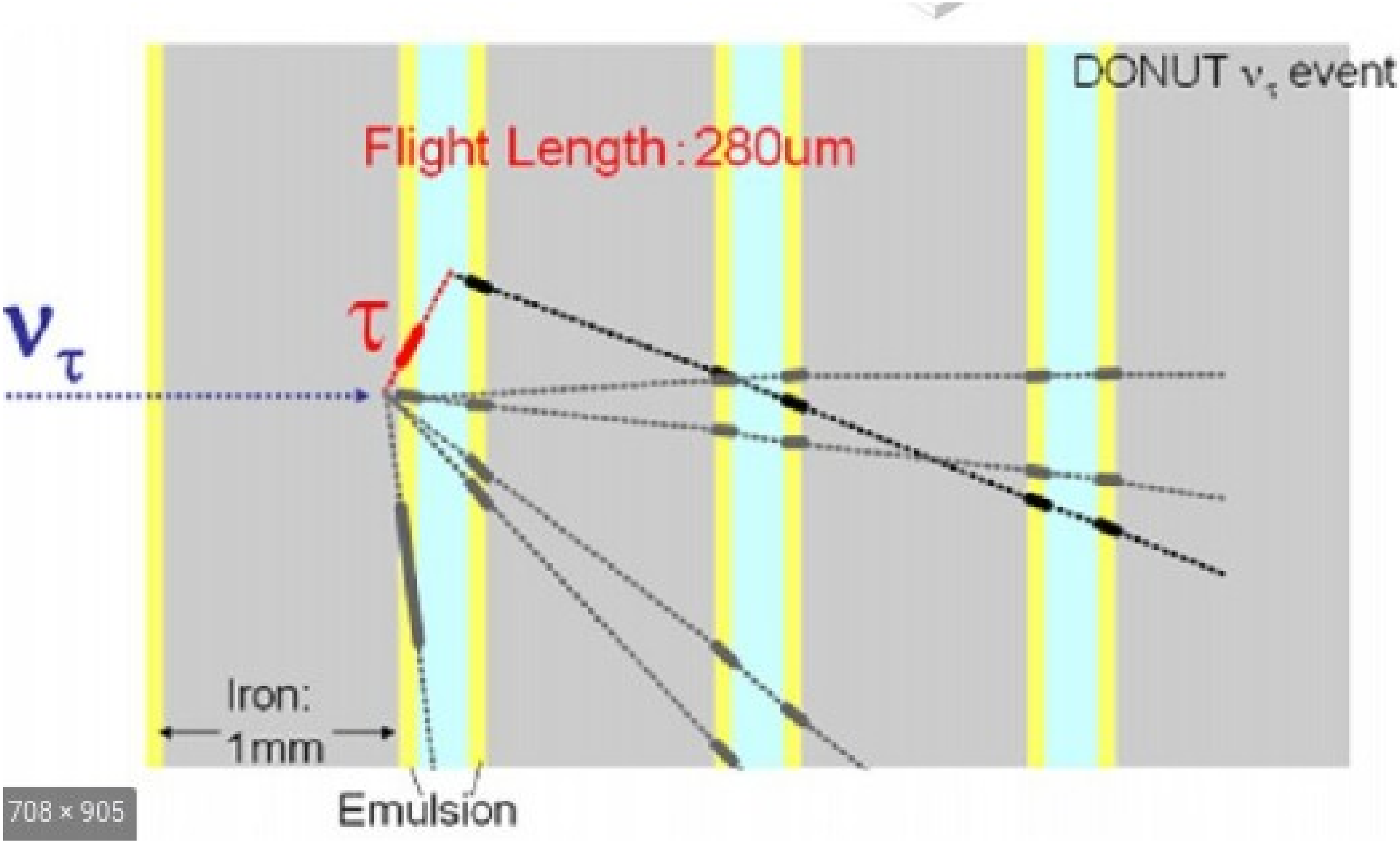


$$D_s \rightarrow \tau + \nu_\tau$$

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

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

Discovery of the ν_τ



Helicity and Chirality

Neutrinos only interact weakly through a V-A interaction
If Neutrinos are massless then

υ : LH Chiral and (mostly) LH helical

$\overline{\upsilon}$: RH Chiral and (mostly) RH helical

Because of ***production***

If Neutrinos have mass then

It is possible to observe a LH chiral neutrino with *right-handed* helicity (but NOT RH chirality)

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

Neutrino Properties

- Electrically neutral and interact only via the weak interaction.
- spin 1/2
- (anti)neutrinos are chirally left(right)-handed (but can be helically right(left)-handed if massive)
- 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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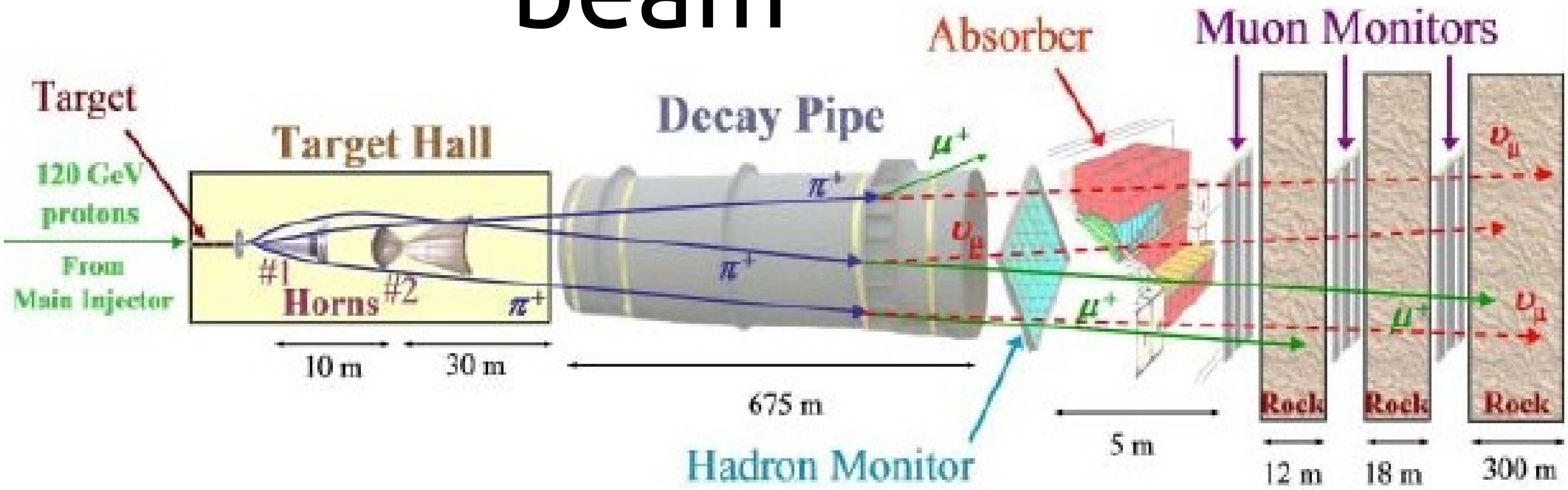
Making Neutrinos

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 ∝ 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
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	0.0-40.0
J-PARC (Japan)	30	1.1E+21	0.48	0.8
*LBNF (Fermilab)***	*60 / 120*	*1.90E+21*	*1.2*	*0.5 – 10.0*
*J-PARC Upgrade***	*30*	*1.60E+22*	*1.5*	*0.6*

**Design parameters – beams still under construction

Targetry

Have to balance competing needs

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

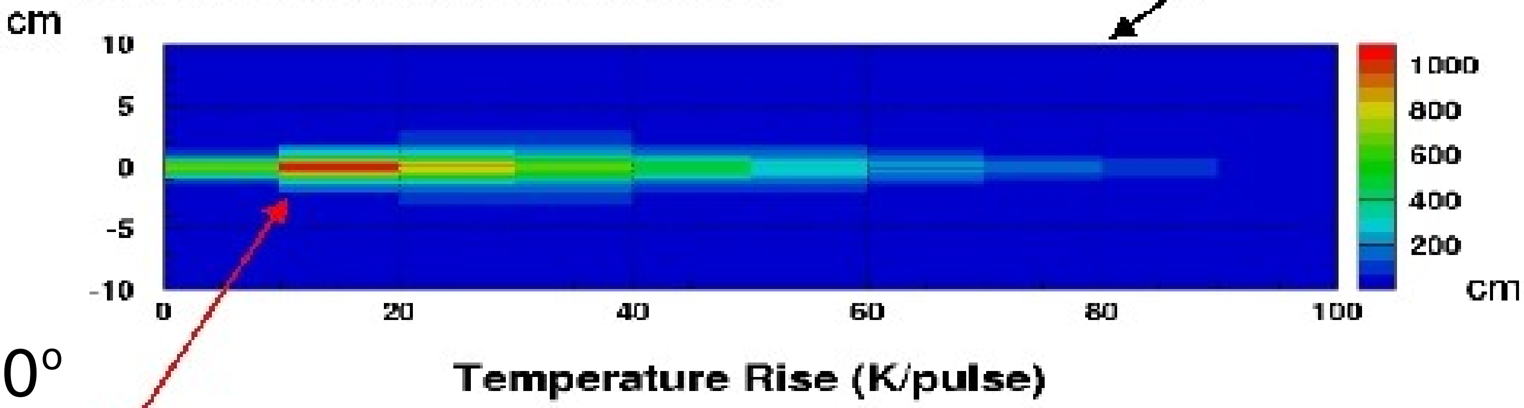
Low Z material (C, Be, Al) for heat properties
Usually around 50 cm to 1 m long
In small segments so that heating won't break the entire thing
Cooling systems needed (air, water, liquid helium)

Targetry

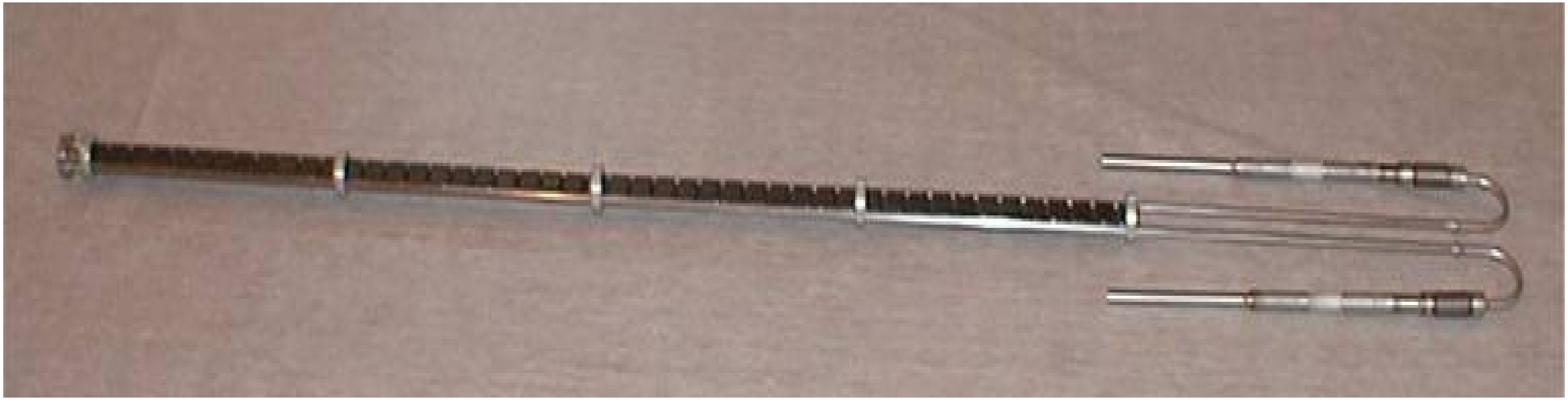
3.3E14 ppp w/ 5μs pulse

When this beam hits an iron block,

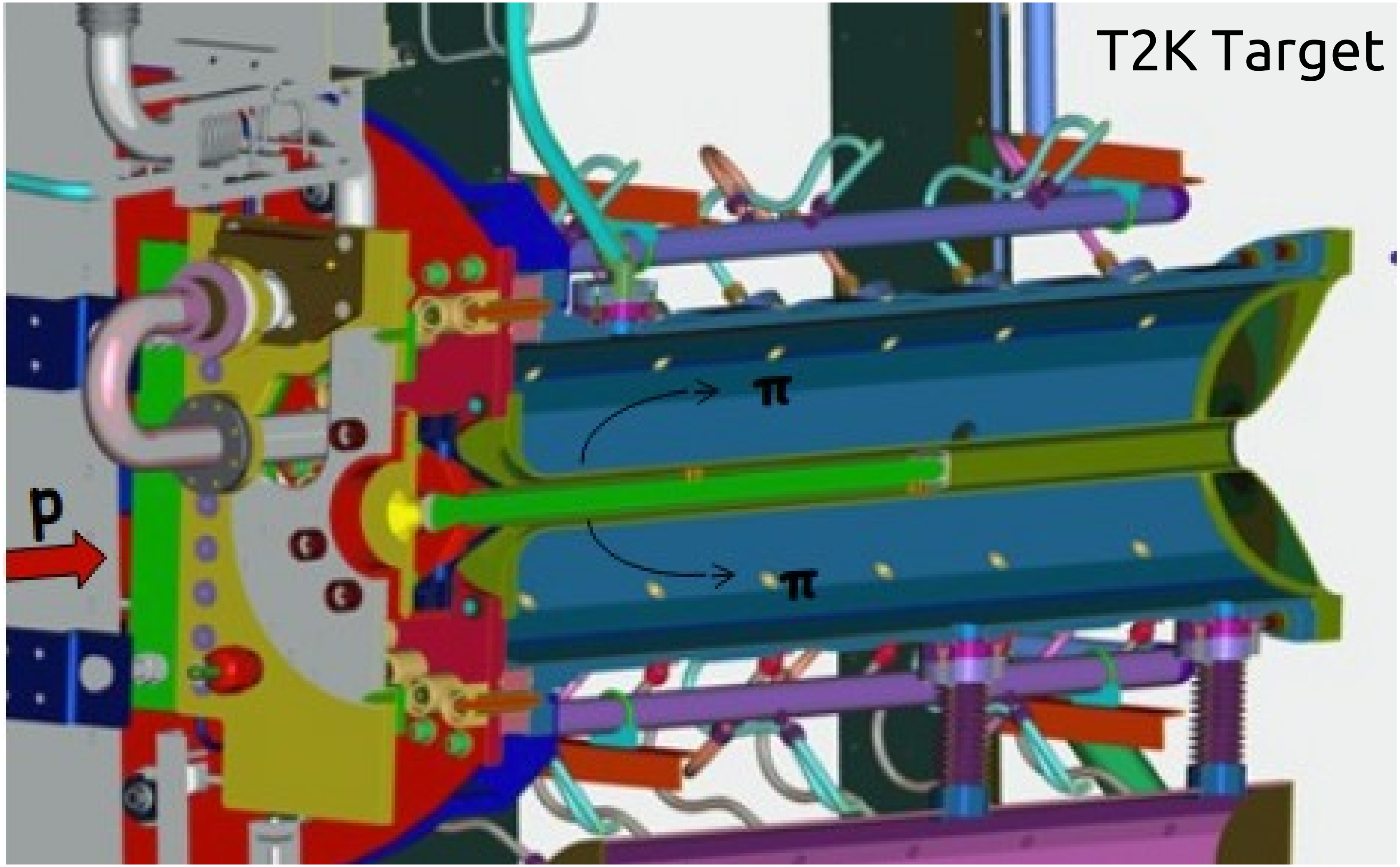
Residual
dose rate
> 1000Sv/h



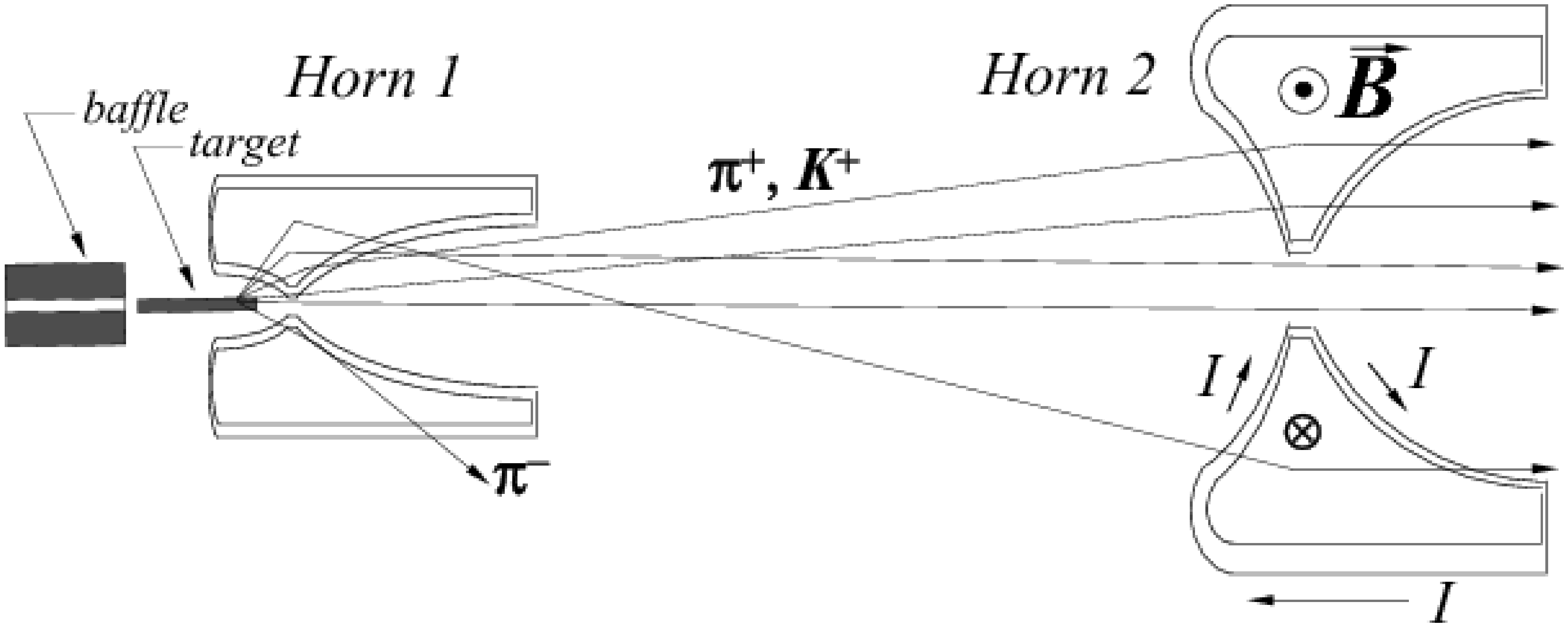
1100°



Target Infrastructure



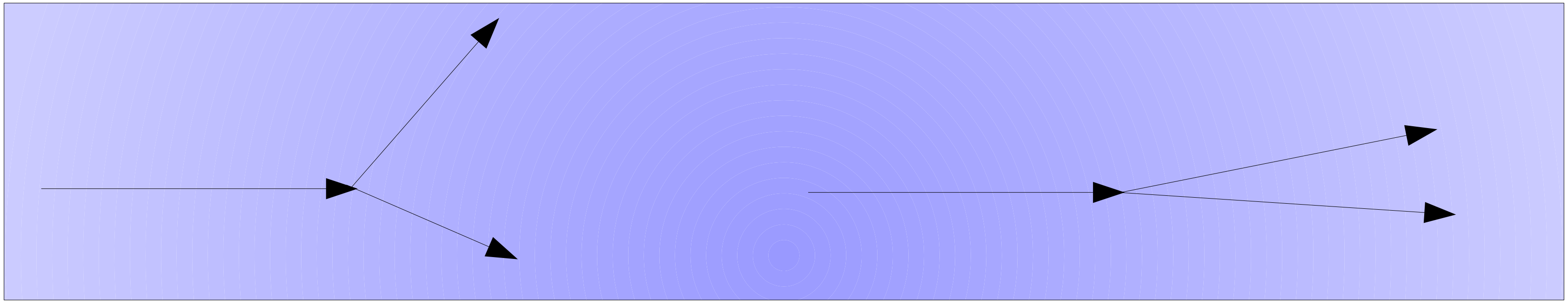
Basics of Horn Focussing



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

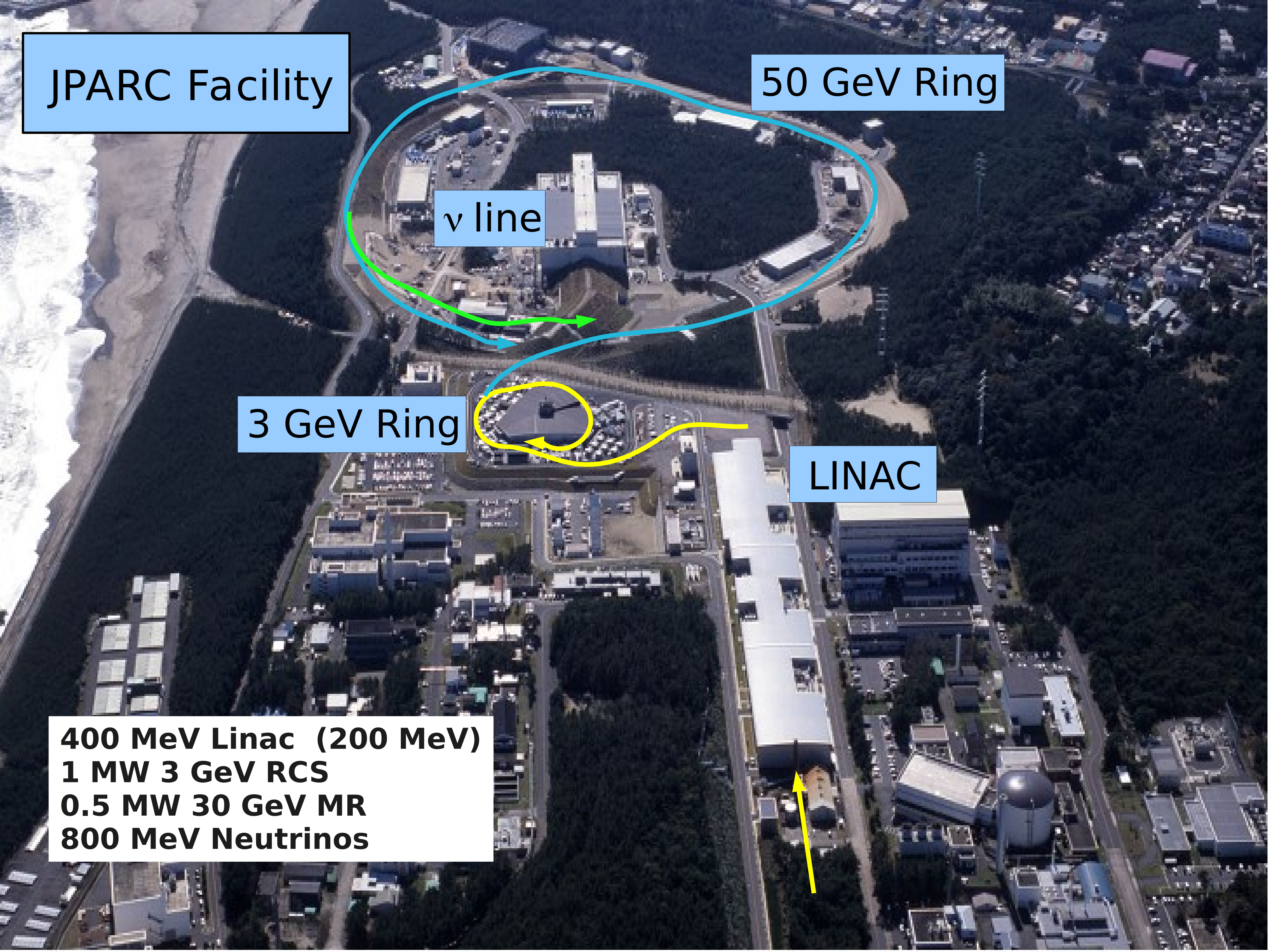
$$P(\pi \rightarrow \nu\,\mu) = 1 - e^{-t/\gamma\tau} = 1 - e^{-L m_\pi / E_\pi \tau}$$

Shorter tunnel, less pion decays

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

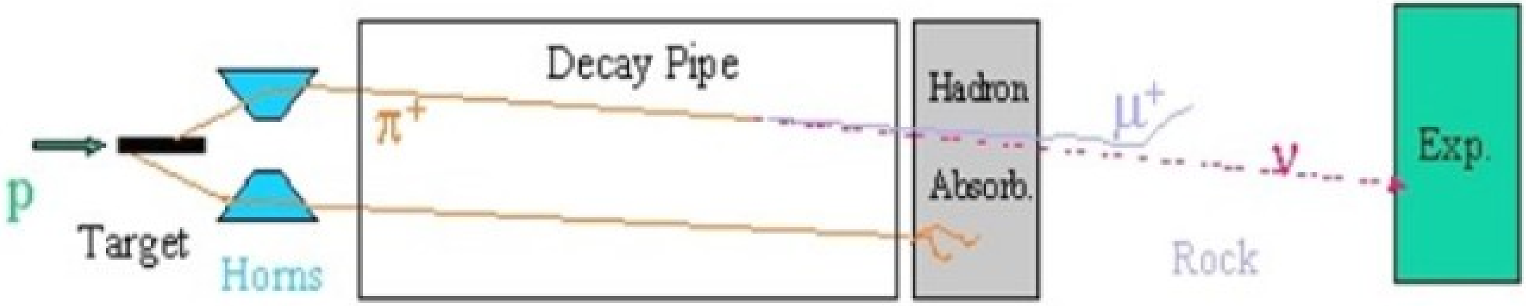
Vacuum? Then more material is needed to hold it. Air? Less material but interactions in decay pipe.

JPARC Facility

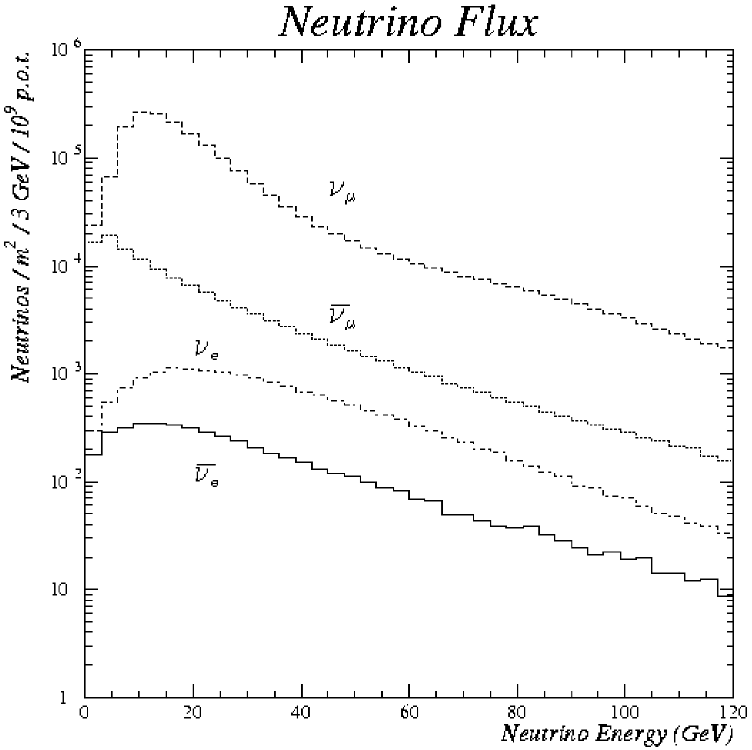


400 MeV Linac (200 MeV)
1 MW 3 GeV RCS
0.5 MW 30 GeV MR
800 MeV Neutrinos

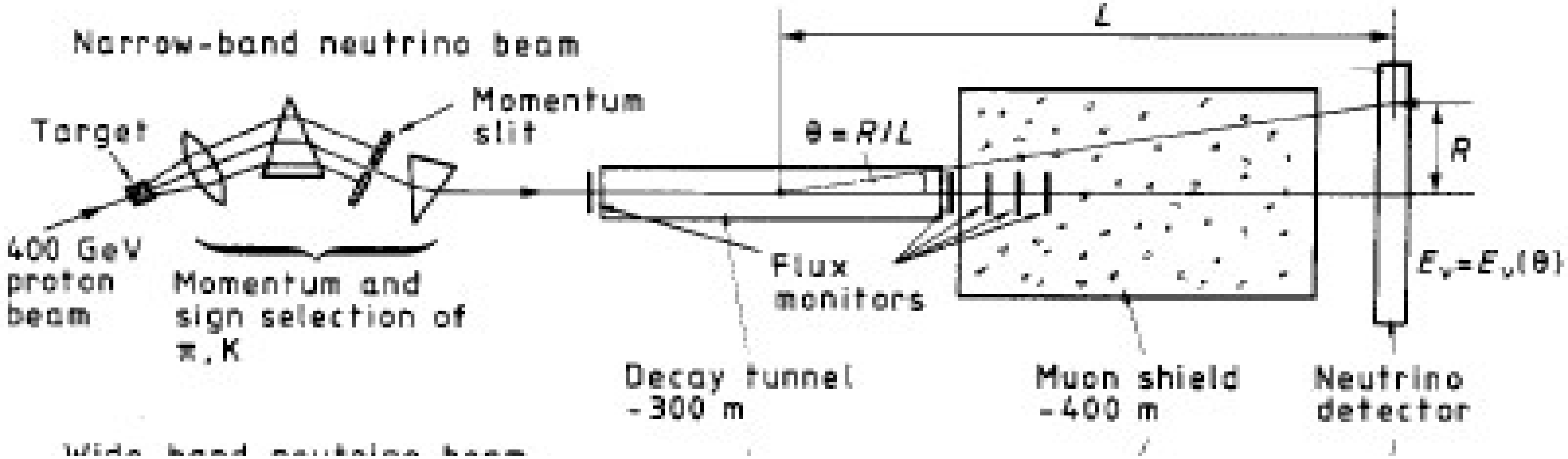
Wide band beams



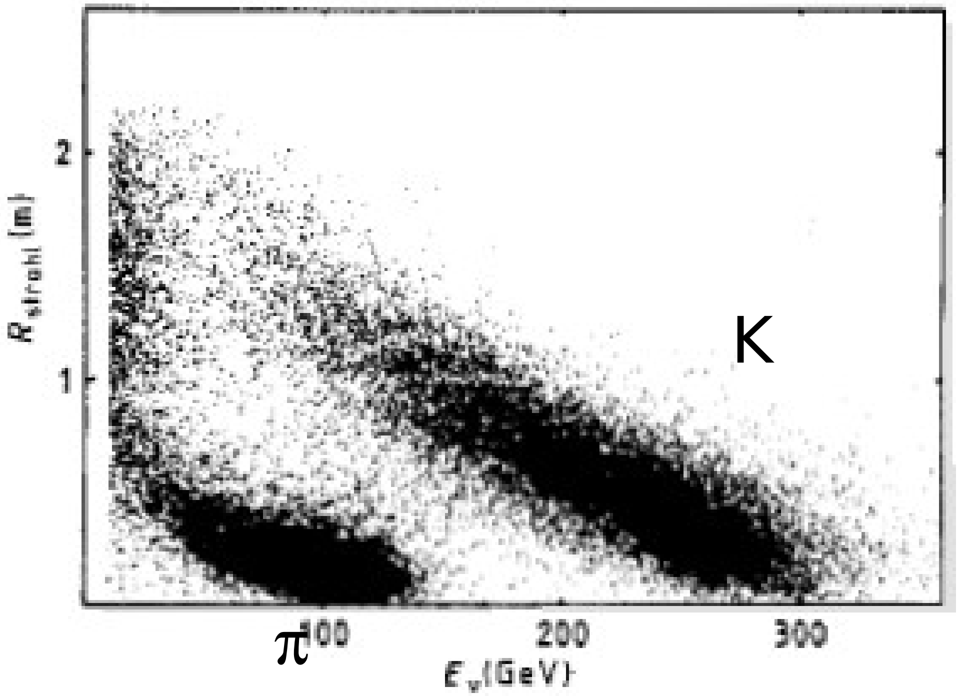
- Large flux of neutrinos.
- Wide range of energies.
- Complex mix of flavours.
- Hard to predict (and measure) neutrino flux.
- Spectrum is a function of radius and decay point



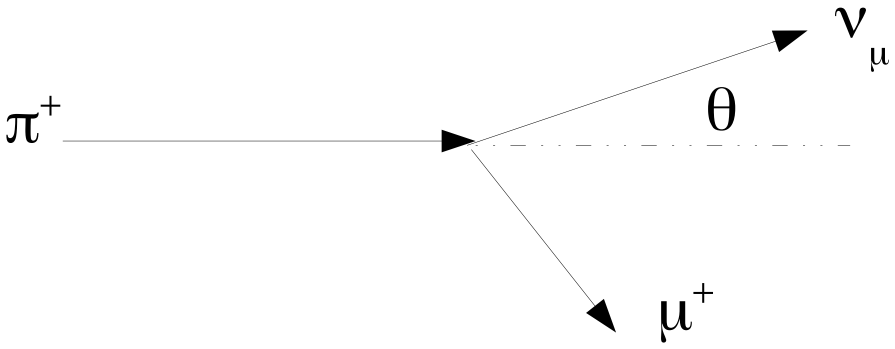
Narrow Band Beams



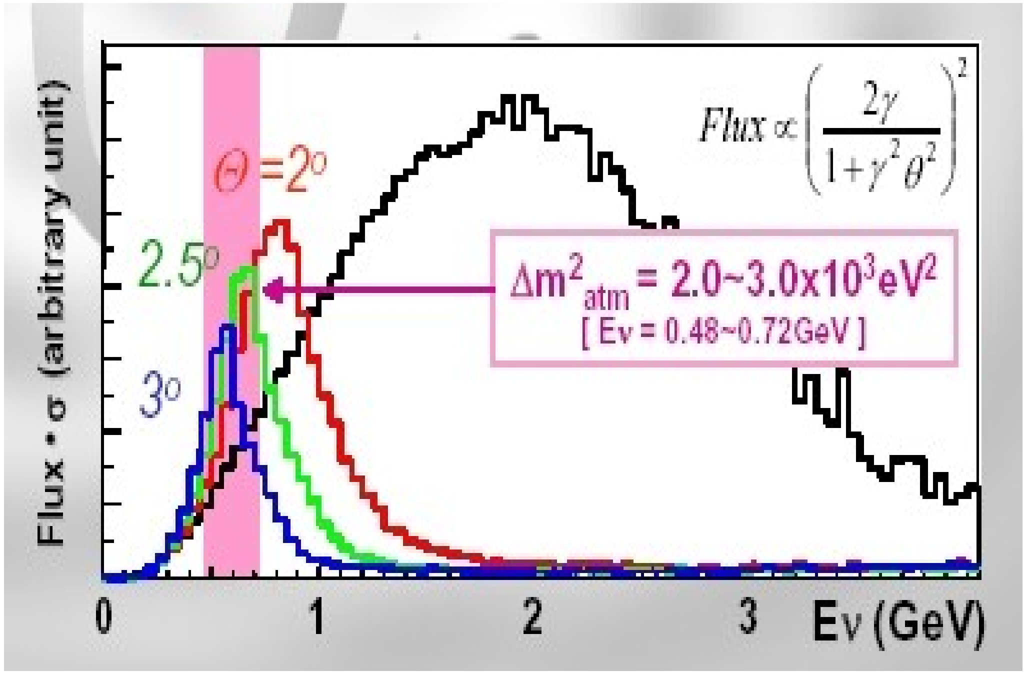
- Flat flux (easy to predict)
- Beam can be tuned to different energies
- flux is 100 times lower than WBB

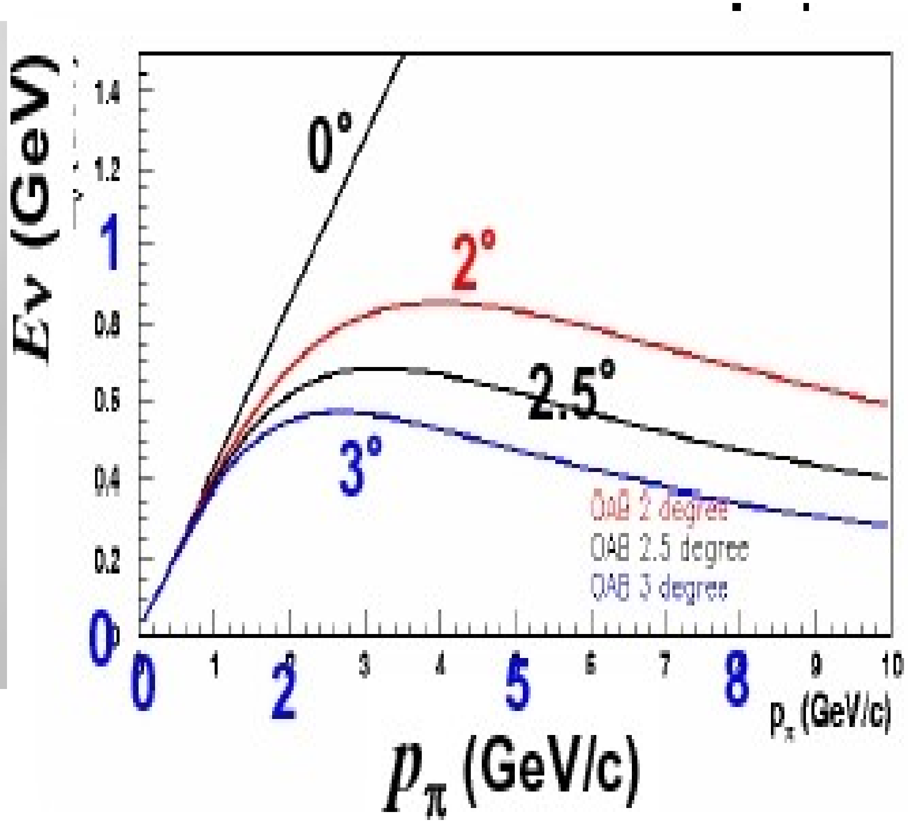


Off-axis beams



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





Neutrino Detection

So, you want to build a neutrino detector?

So, you want to build a neutrino detector?

Ha ha. Good one. 😂

So, you want to build a neutrino detector?

~~Ha ha. Good one. 😂~~

Oh you were being serious!? 😬

Alrighty then, riddle me this...

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

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- What sort of backgrounds do have to deal with?
  - More influence on technology – usually conflicting with signal requirements.

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- What do you want to measure?
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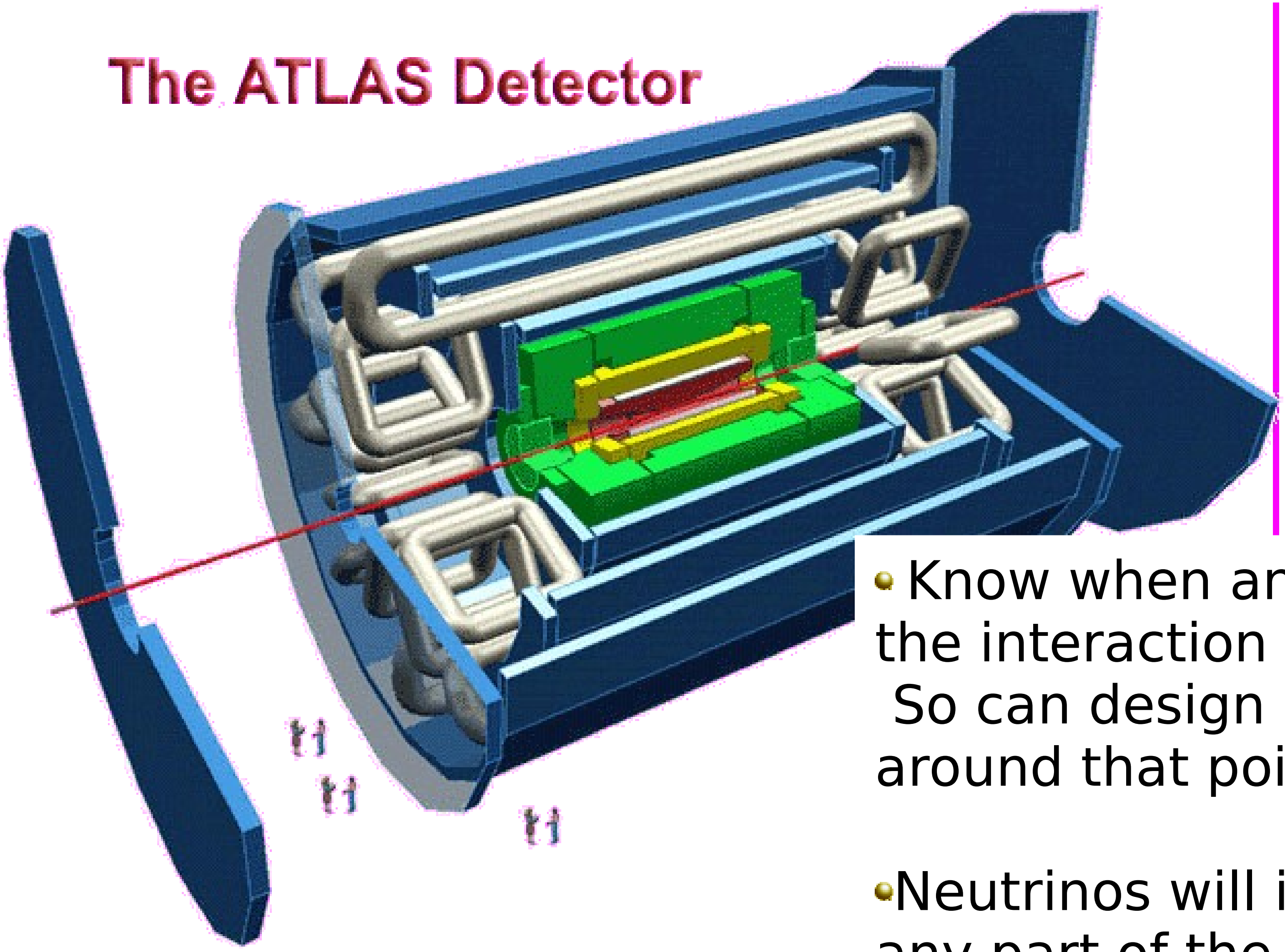
- What sort of backgrounds do have to deal with?
  - More influence on technology – usually conflicting with signal requirements.
- How much  do you have?

Usual collider detector



- Know when and where the interaction will occur. So can design a detector around that point
- Neutrinos will interact in any part of the detector

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

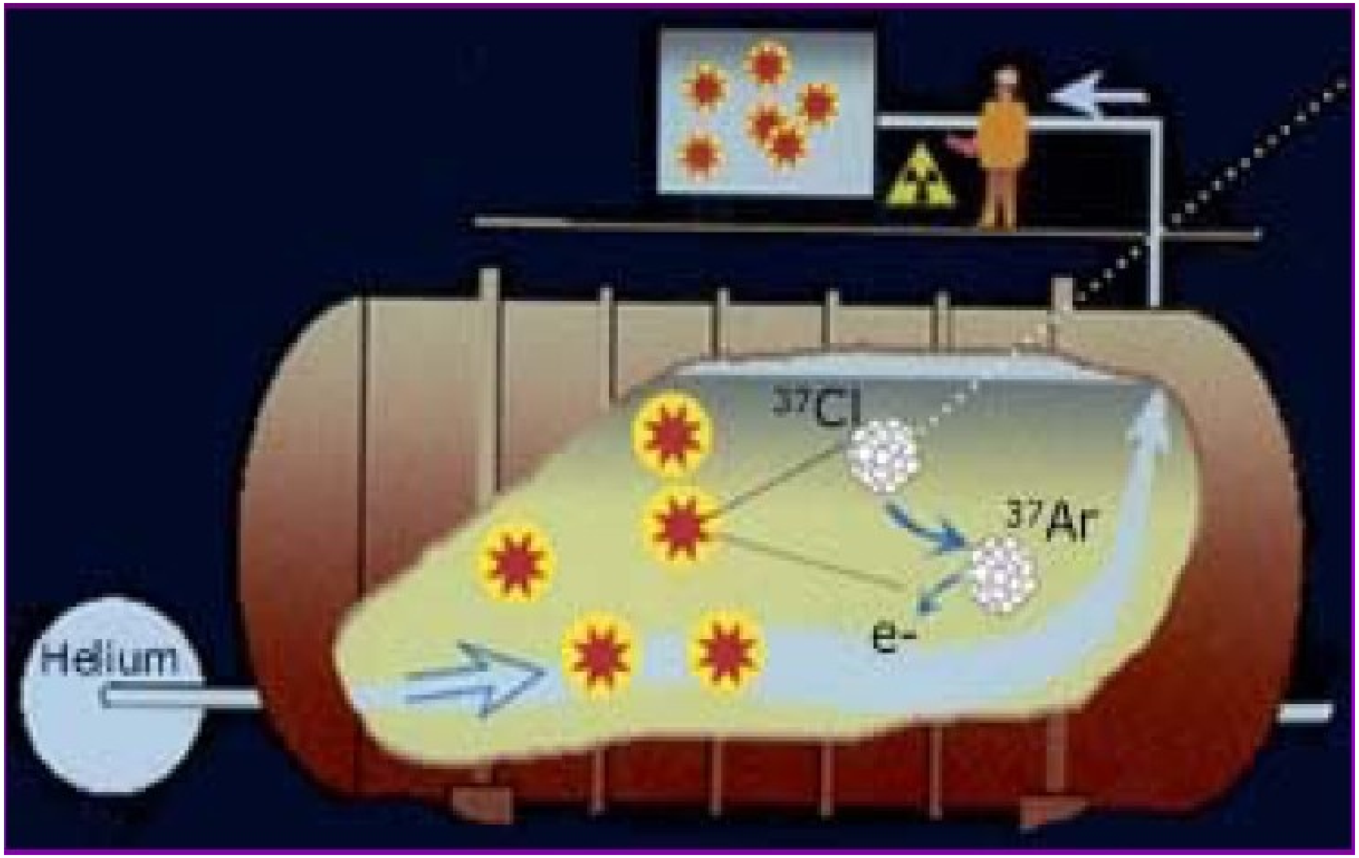
$$\nu_e + Cl^{37} \rightarrow Ar^{37} + e^- \qquad \nu_e + Ga^{71} \rightarrow \mathrm{Ge}^{37} + e^-$$

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
to 1994

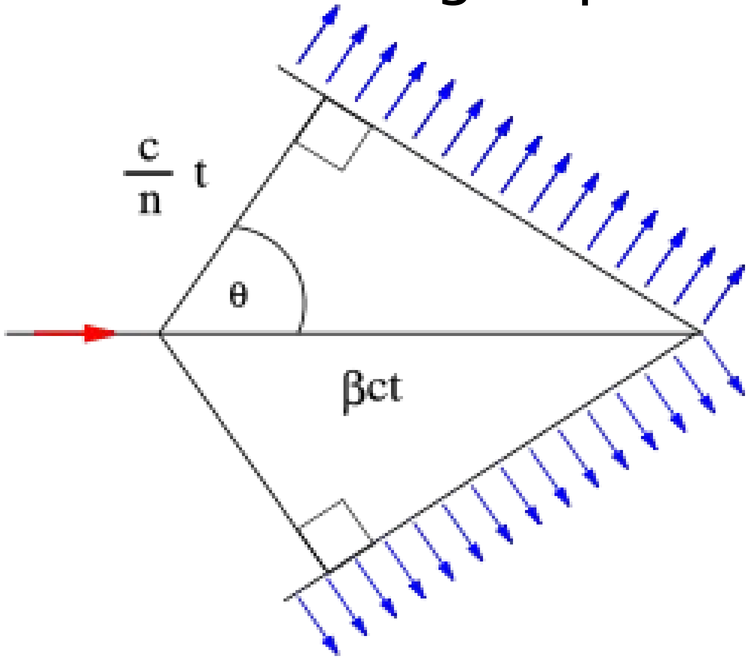
Individual argon atoms are captured and counted.

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.



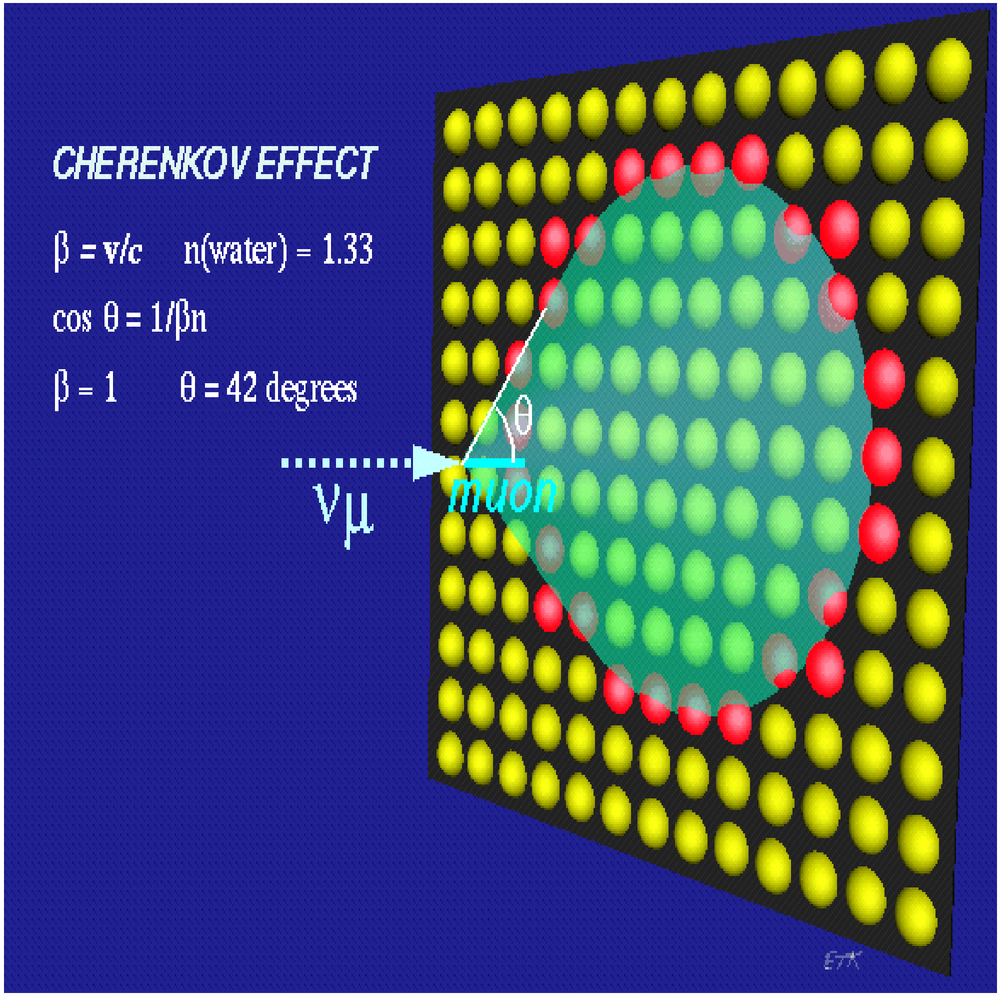
If a charged particle moves through a material with β > 1/n it produces an EM shockwave at a particular angle.

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

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

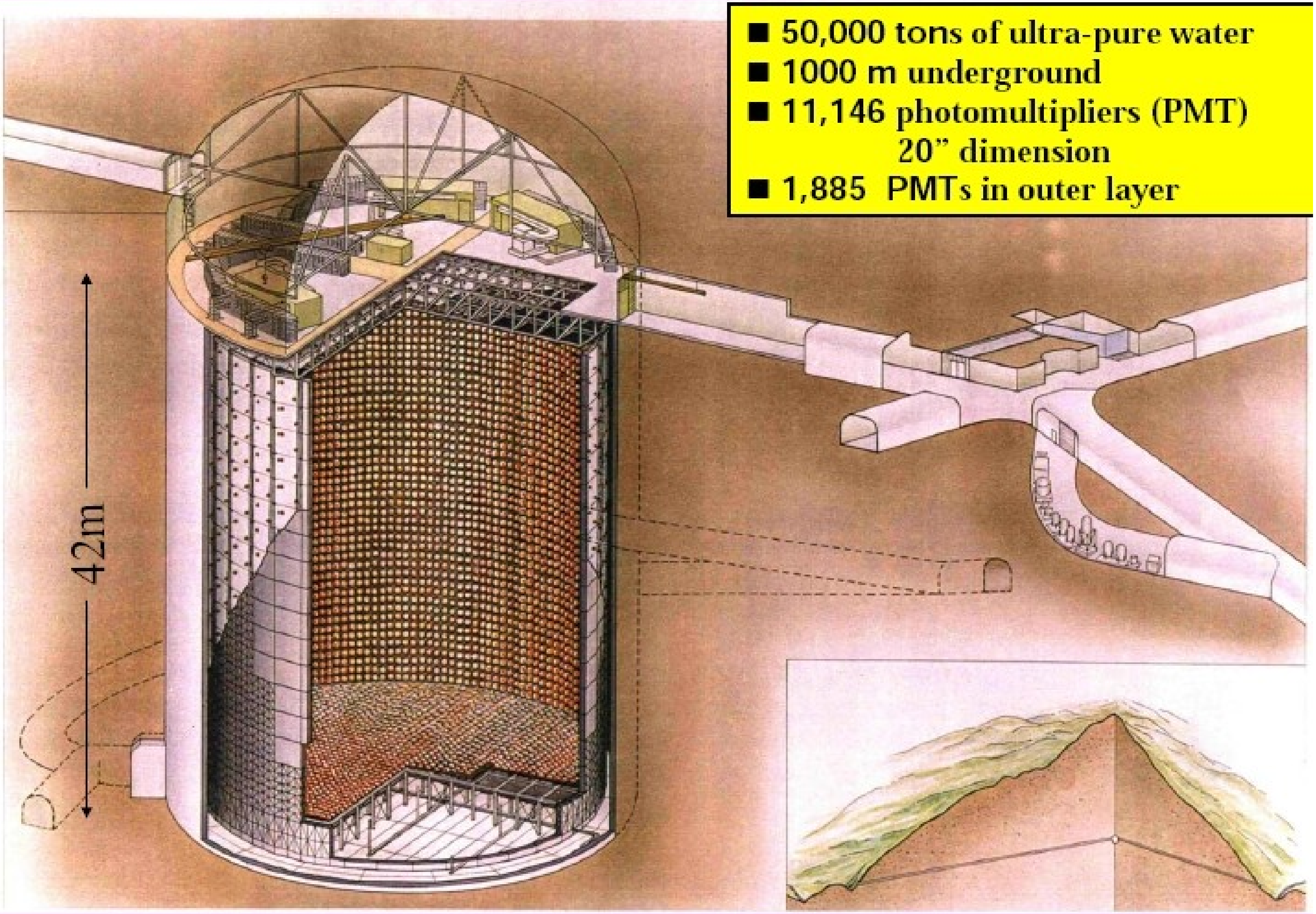
*See Antonis' lecture on Friday for more uses of the Cerenkov technique

Principle of operation

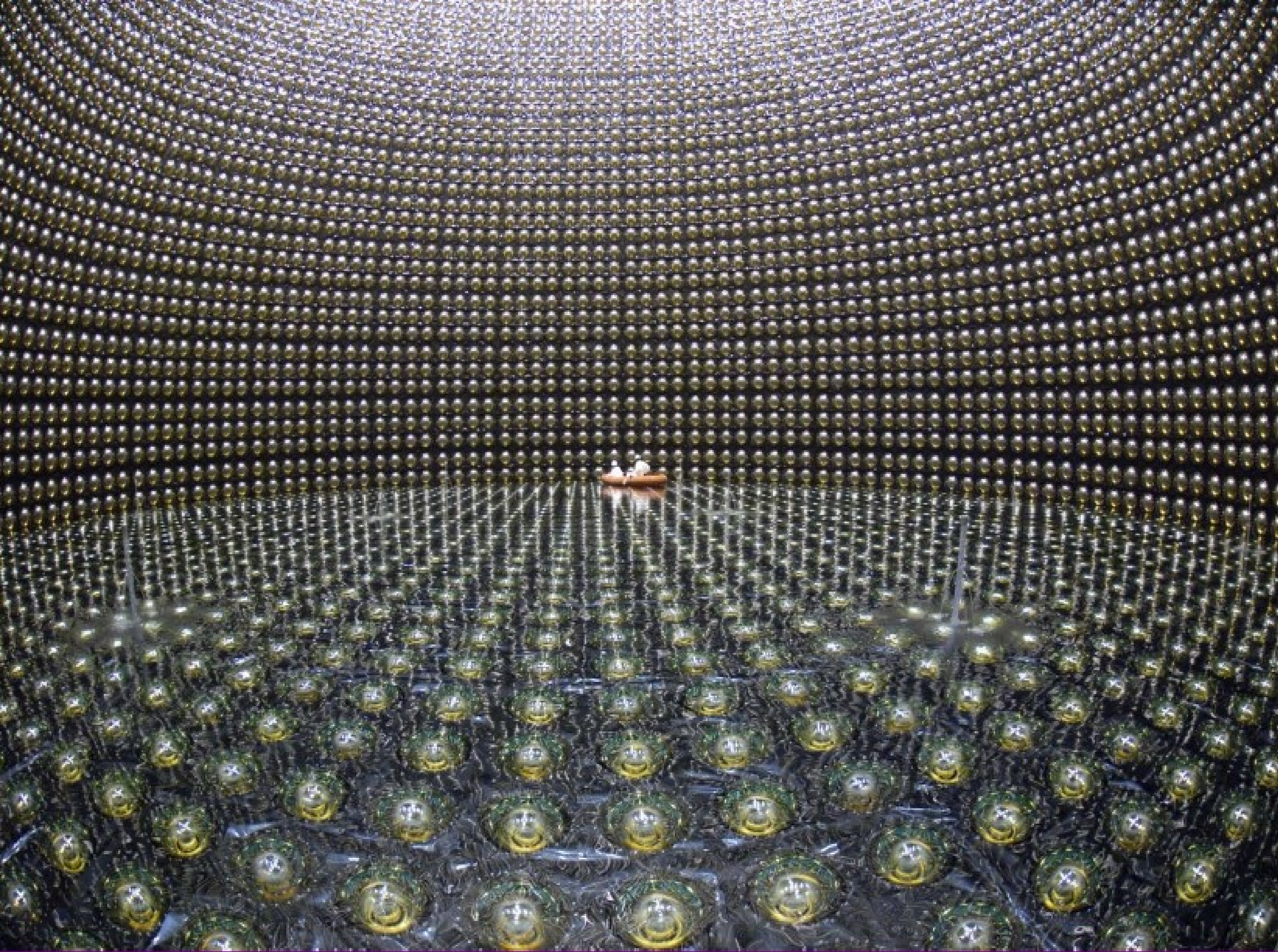


- Cerenkov light detected as a ring or circle by PMTs
- Vertex from timing
- Direction from cone
- Energy from summed light
- No neutrals or charged particles under Cerenkov threshold
- Low multiplicity events

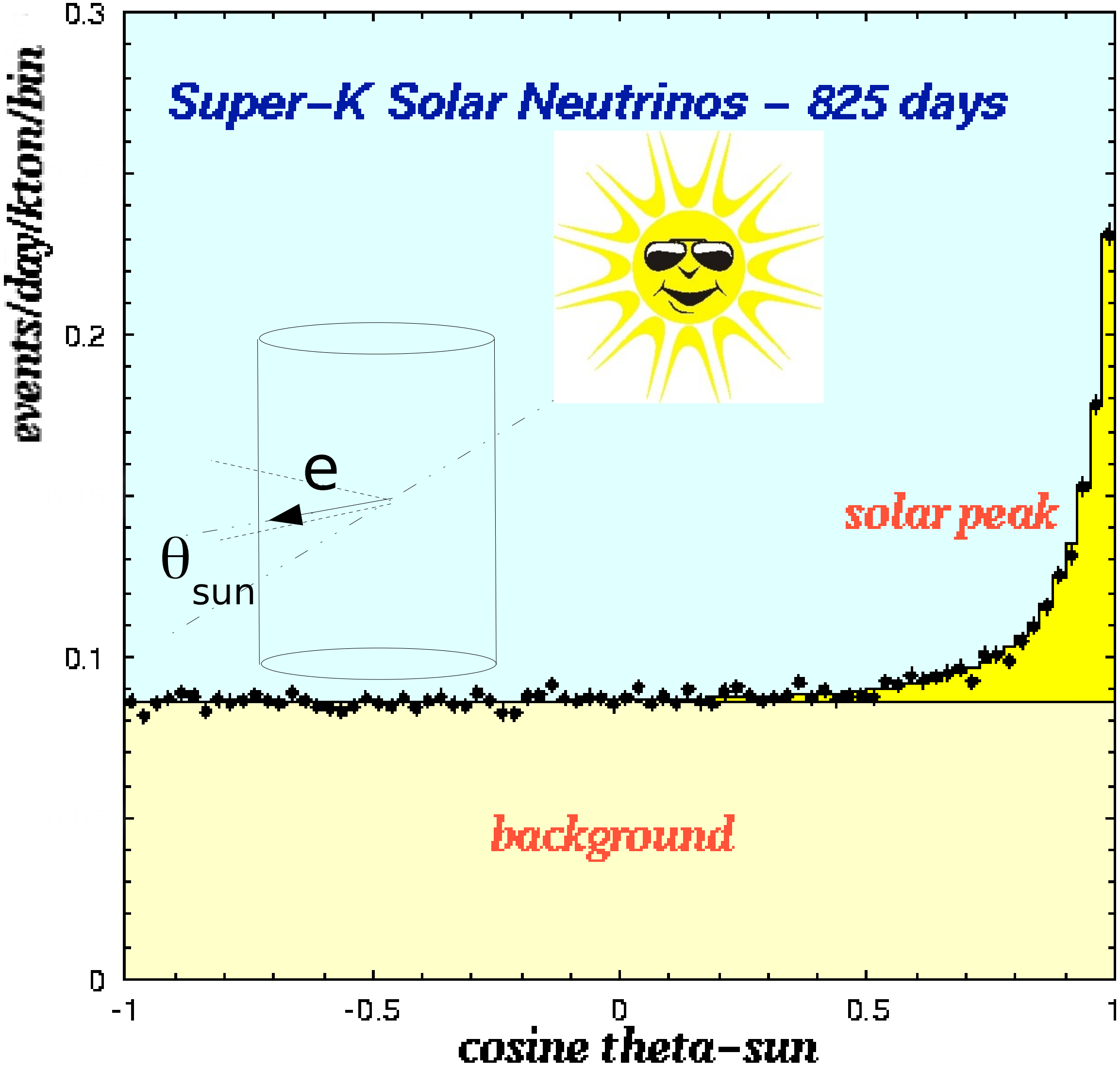
Super-Kamiokande



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

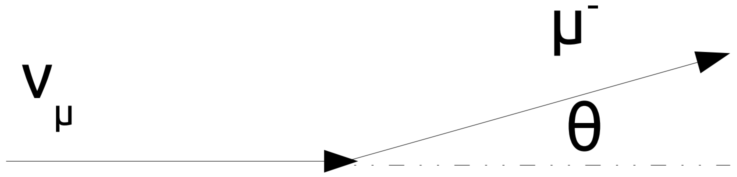


Directionality

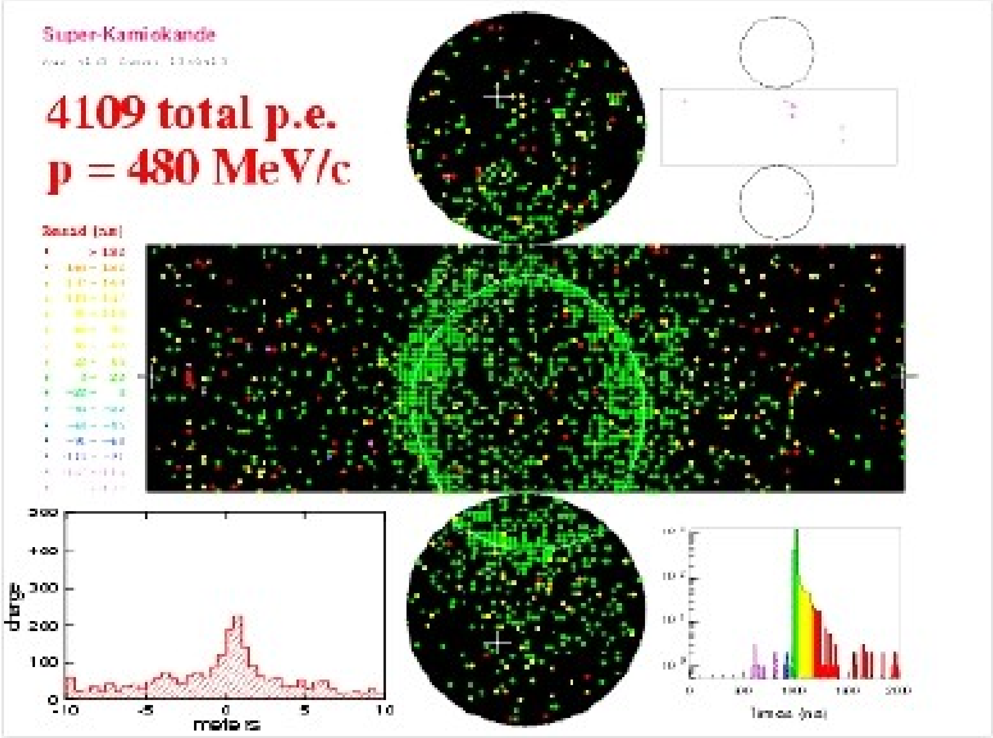


For simple events , the direction of the ring can be used to point back to the neutrino source

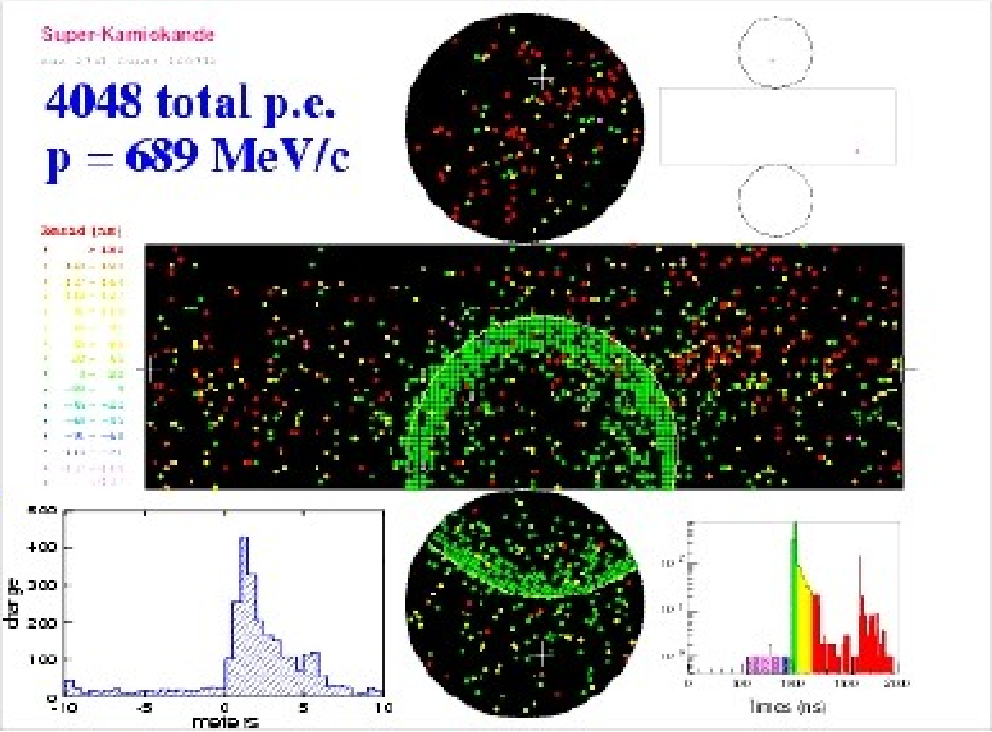
Proof that these neutrinos were coming from the sun



e–like



μ–like



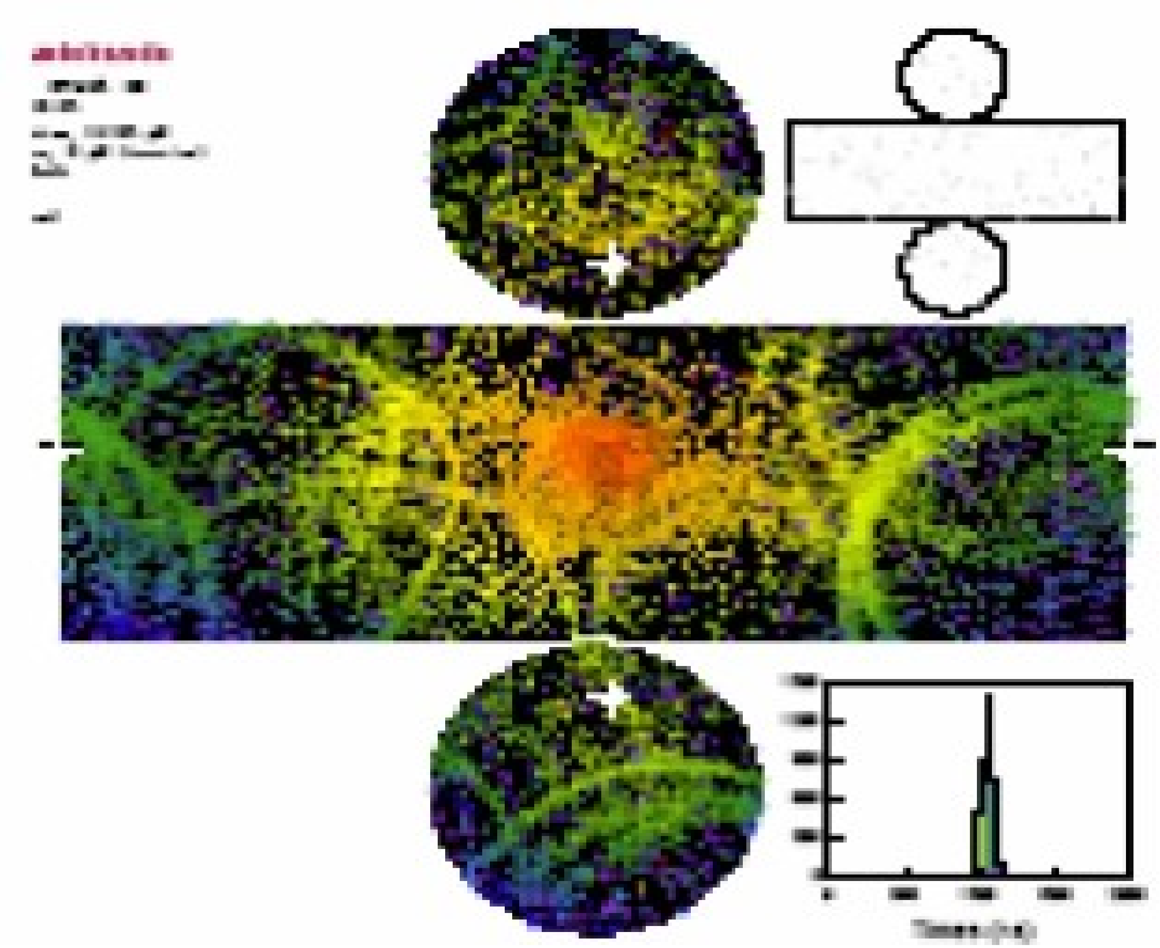
Electron-like : has a fuzzy ring

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

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

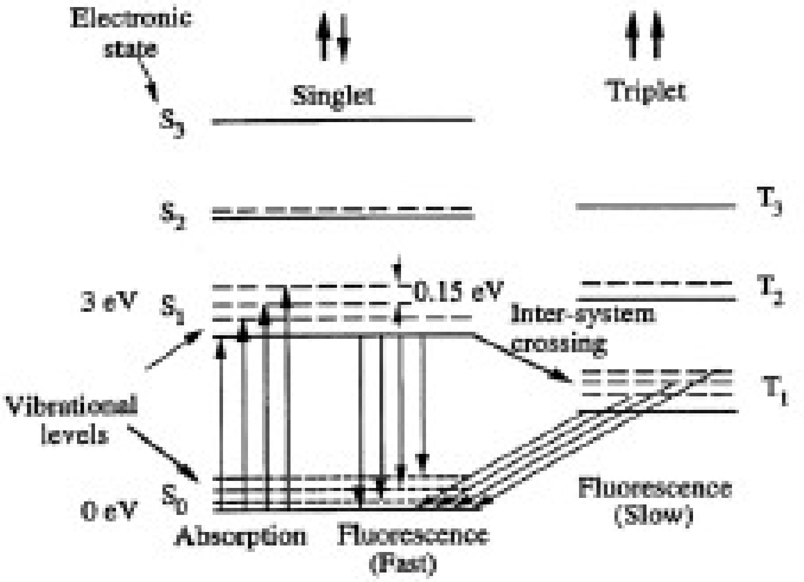
Problems

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



Scintillator Detectors

Light emission following ionisation



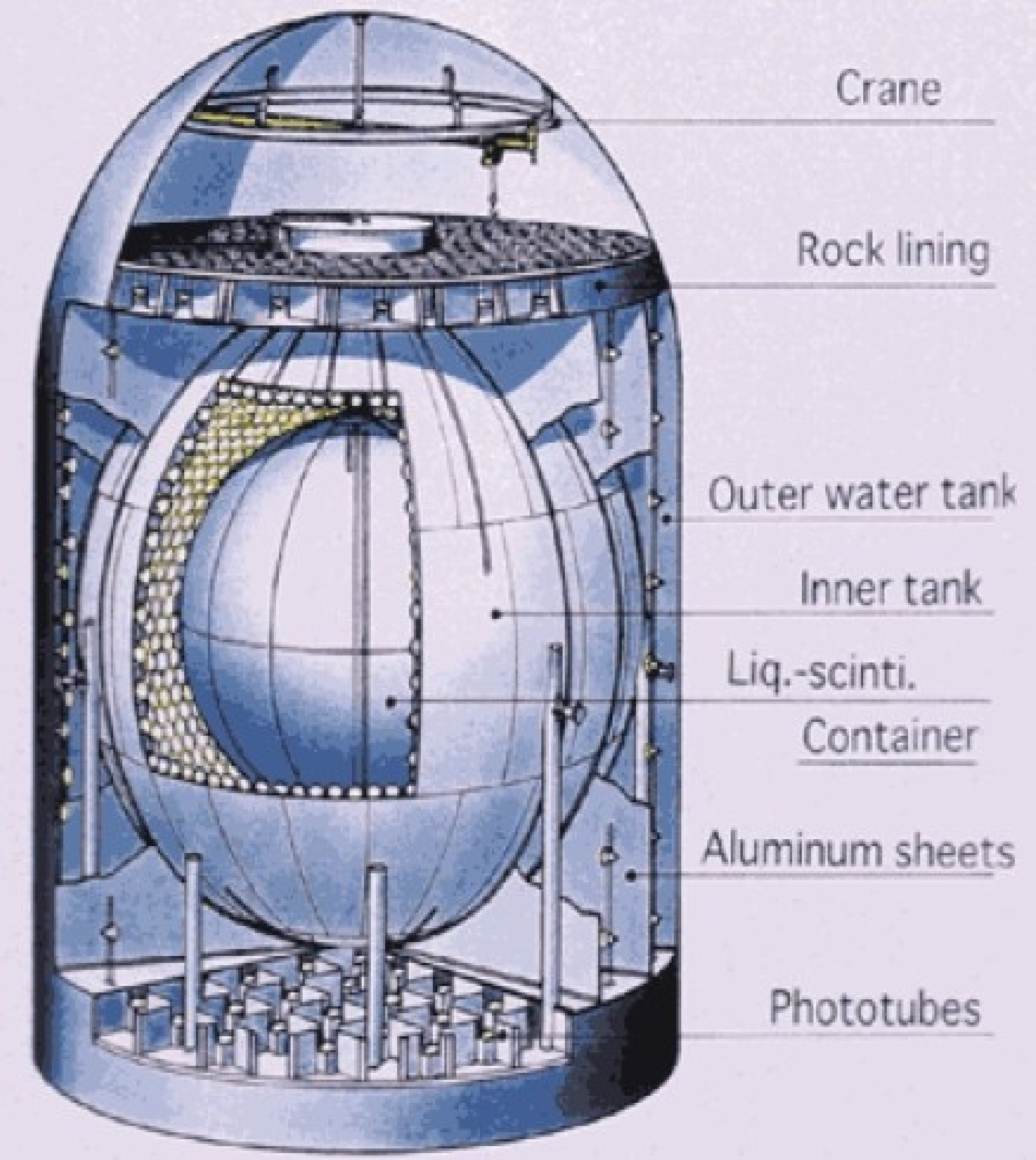
Organic liquids and plastics

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



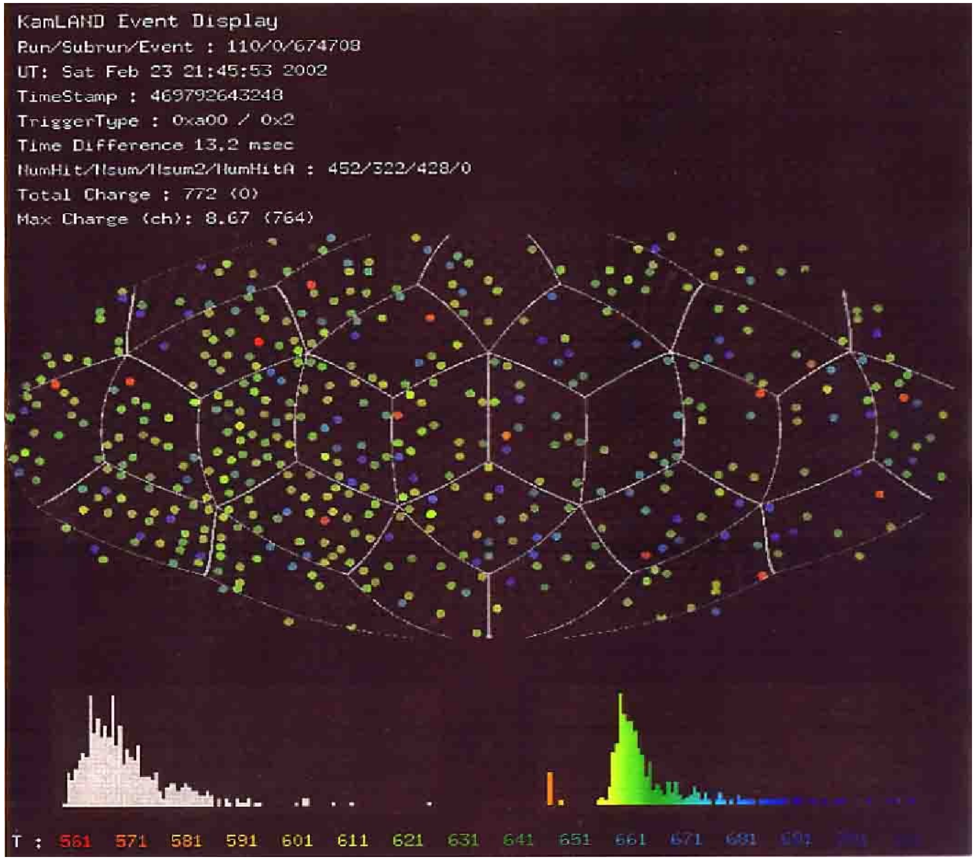
- External container filled with 3.2 kton H_2O
- Inner sphere filled with 2 kton of mineral oil
- Inside transparent balloon filled with 1 kton of liquid scintillator
- Located 1km deep in the Kamioka mine, just up the street from Super-Kamiokande
- Very pure – background is a major problem.

Event Displays

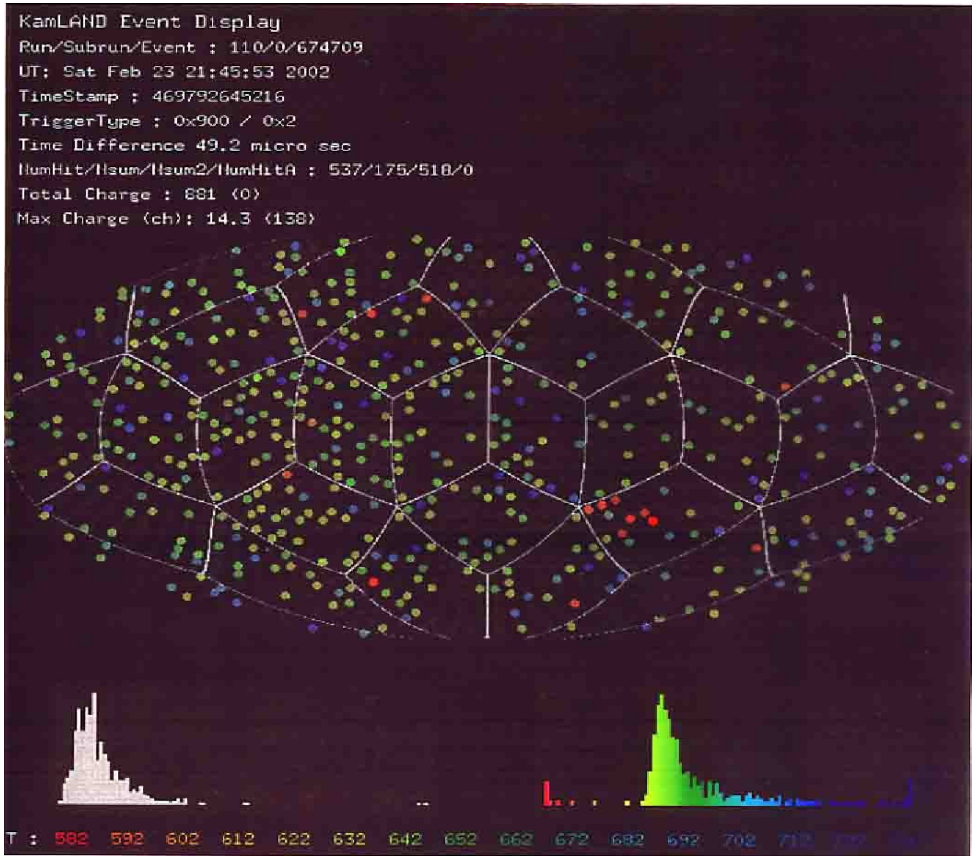
$\overline{\nu}_e + p \rightarrow e^{+} + n$

200 ms later

$n + p \rightarrow d + \gamma$



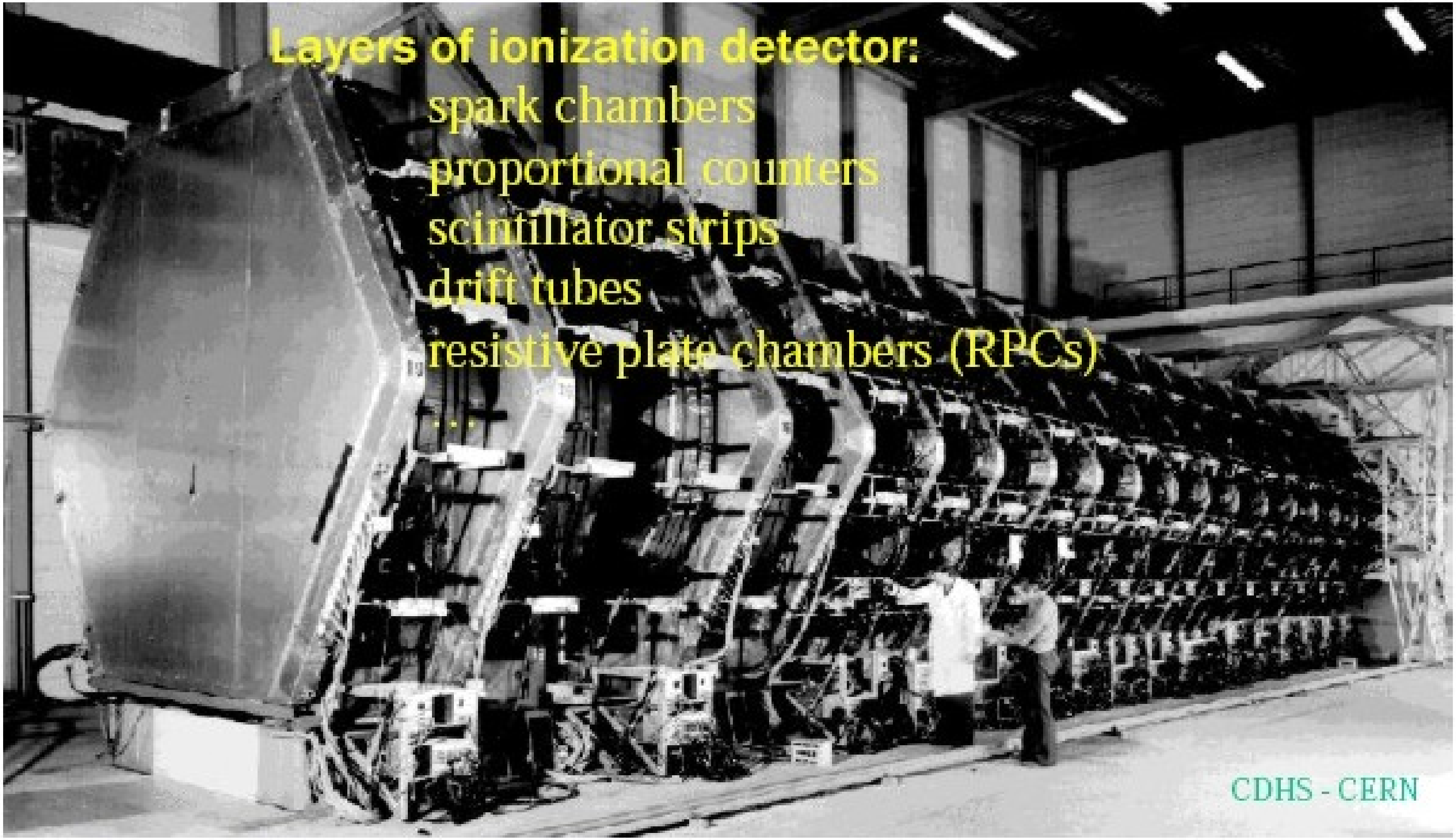
```
KamLAND Event Display
Run/Subrun/Event : 110/0/674708
UT: Sat Feb 23 21:45:53 2002
TimeStamp : 469792643248
TriggerType : 0xa00 / 0x2
Time Difference 13.2 msec
NumHit/Nsum/Nsum2/NumHitA : 452/322/428/0
Total Charge : 772 (0)
Max Charge (ch): 8.67 (764)
```



```
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:

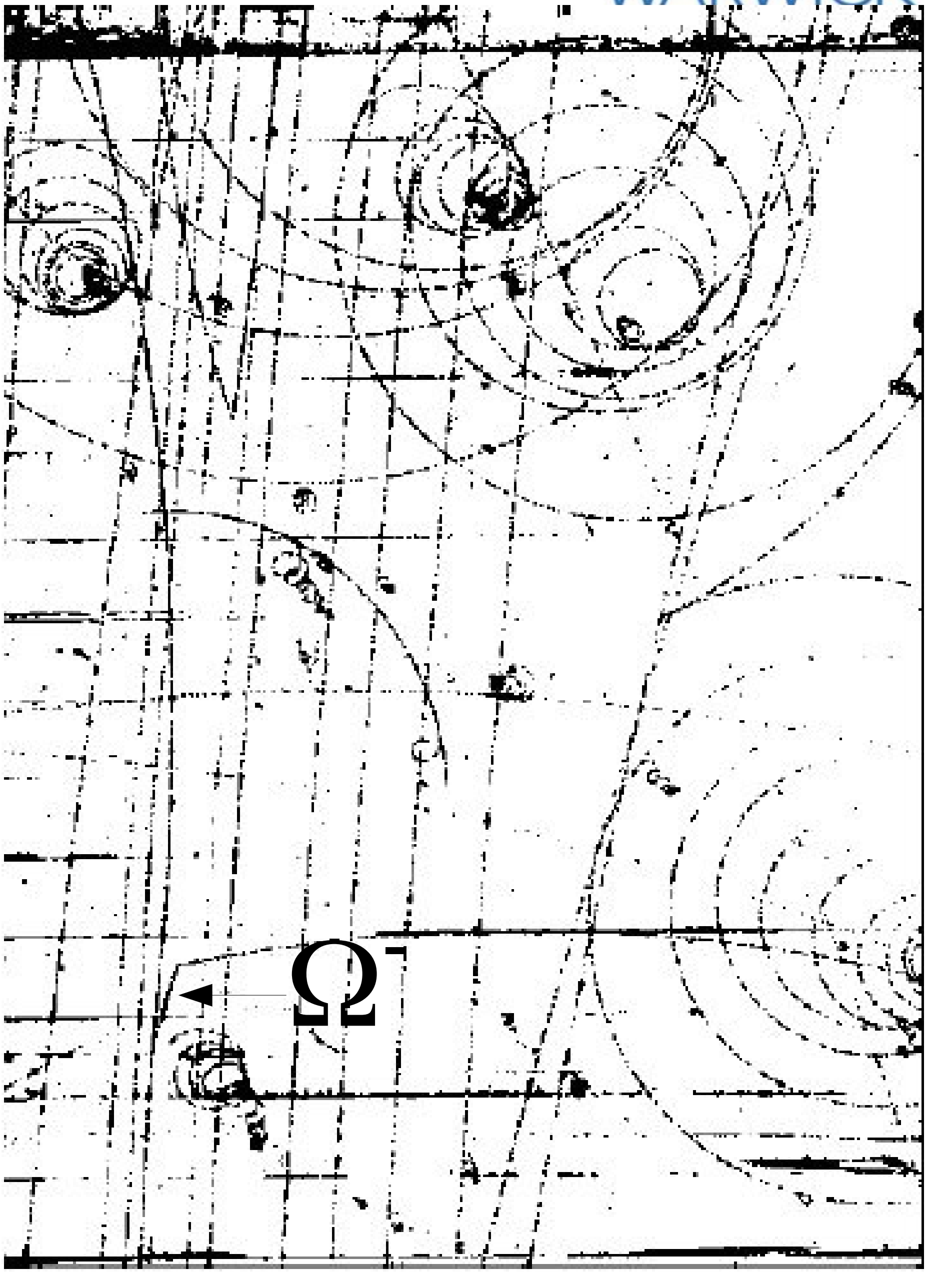
- spark chambers
- proportional counters
- scintillator strips
- drift tubes
- resistive plate chambers (RPCs)
- ...

CDHS - CERN

Neutrino Detectors - Ed Kearns - Fermilab/KEK Neutrino Summer School - 2007

Tracking Chambers

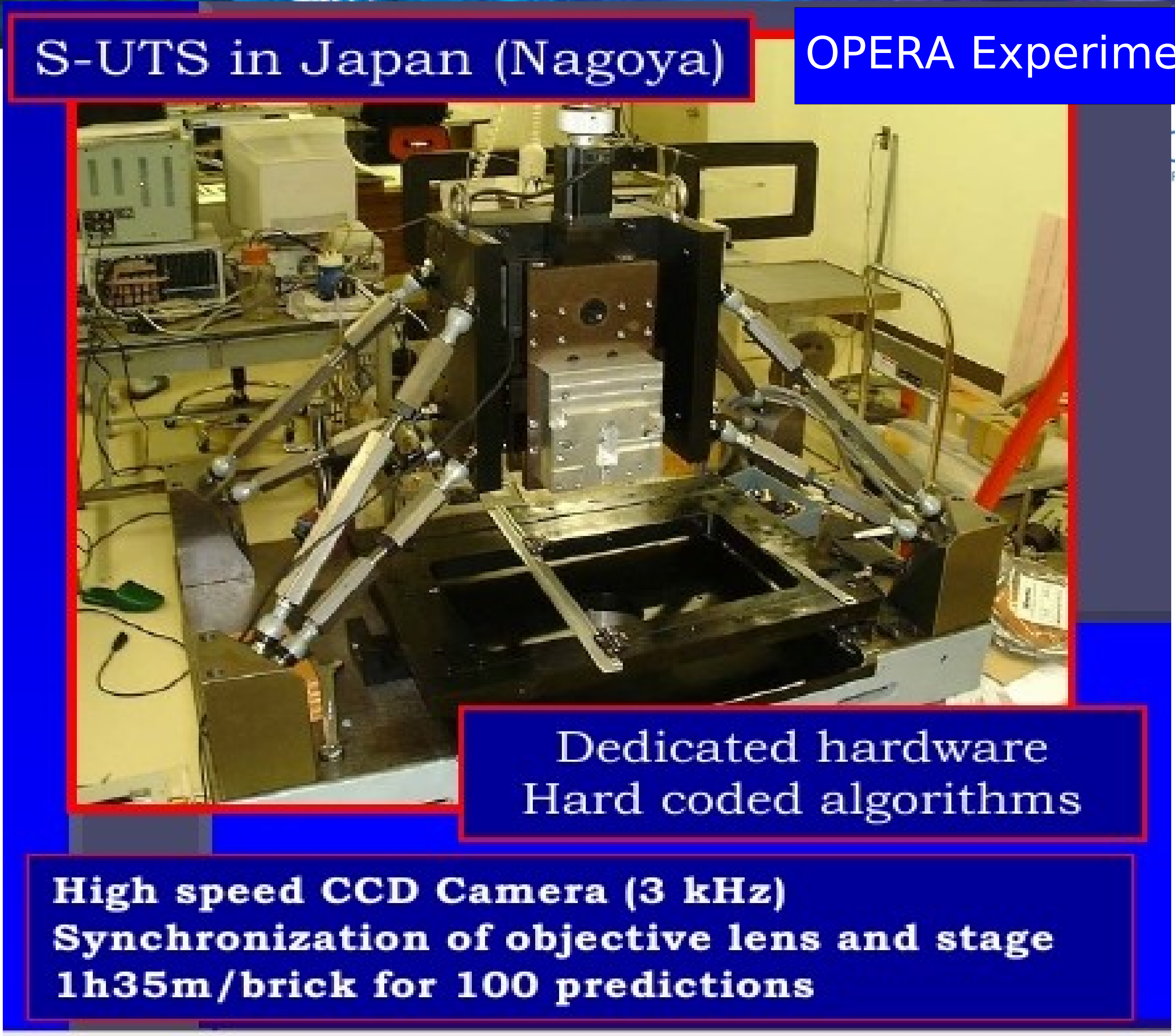
BEBC Chamber



The LBL Frankenstein

Scan 24,000 events per year and required 5 people to keep operating

OPERA Experiment



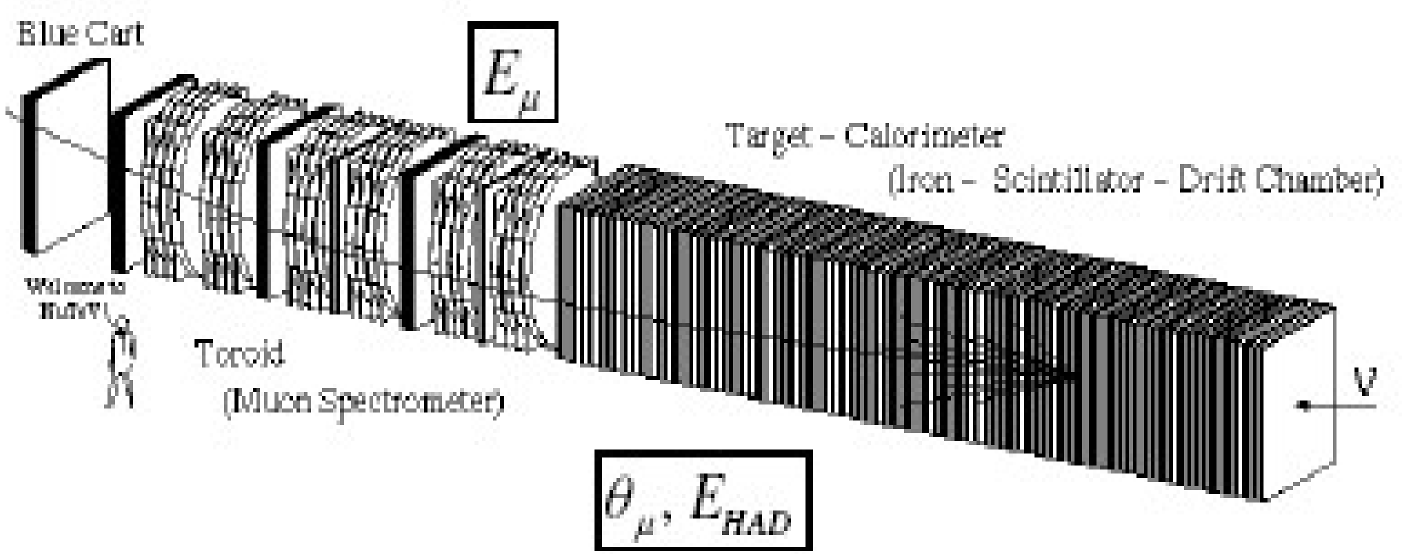
S-UTS in Japan (Nagoya)

Dedicated hardware
Hard coded algorithms

High speed CCD Camera (3 kHz)
Synchronization of objective lens and stage
1h35m/brick for 100 predictions

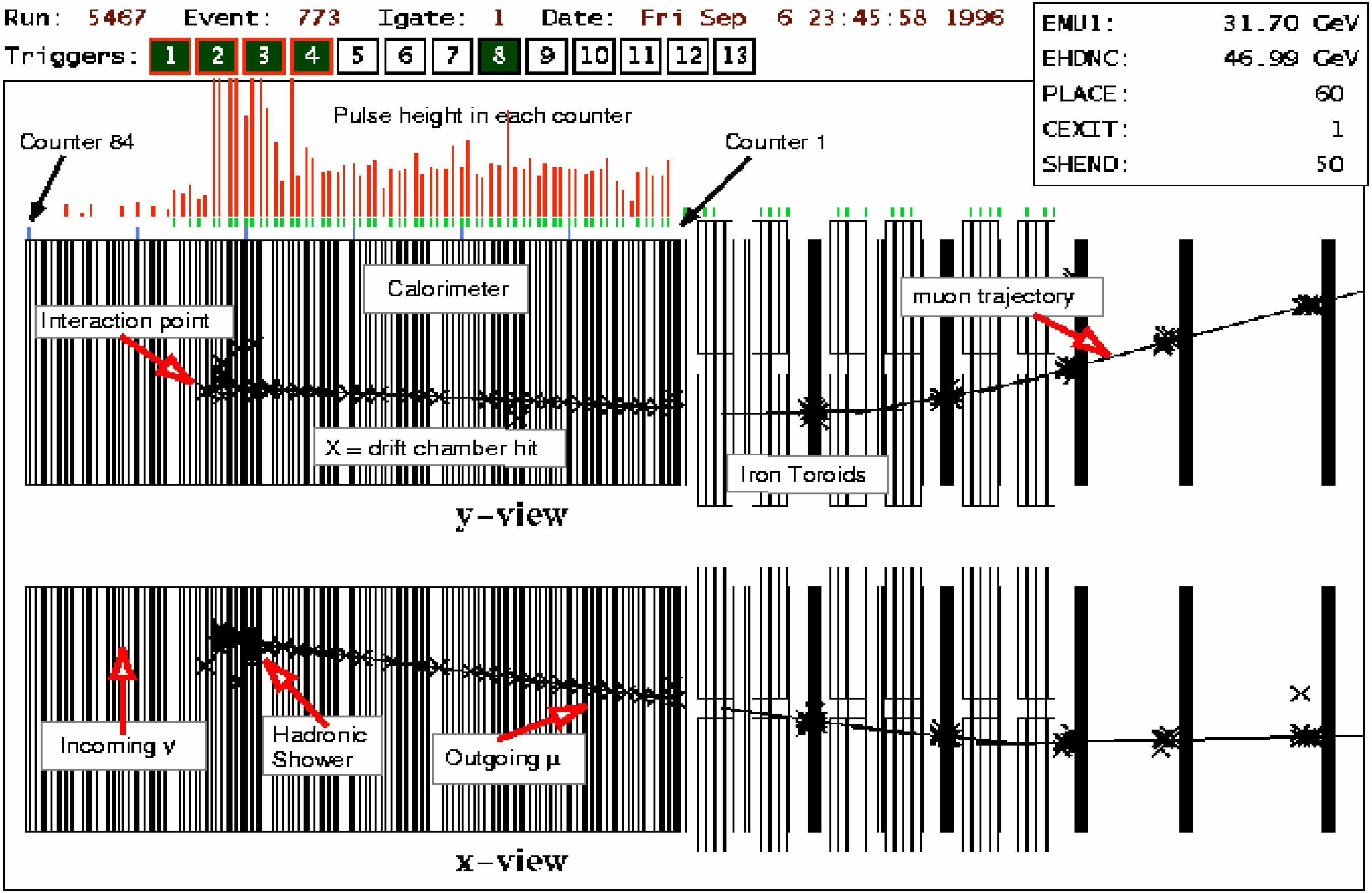
NUTEV

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



- 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 Event Display



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

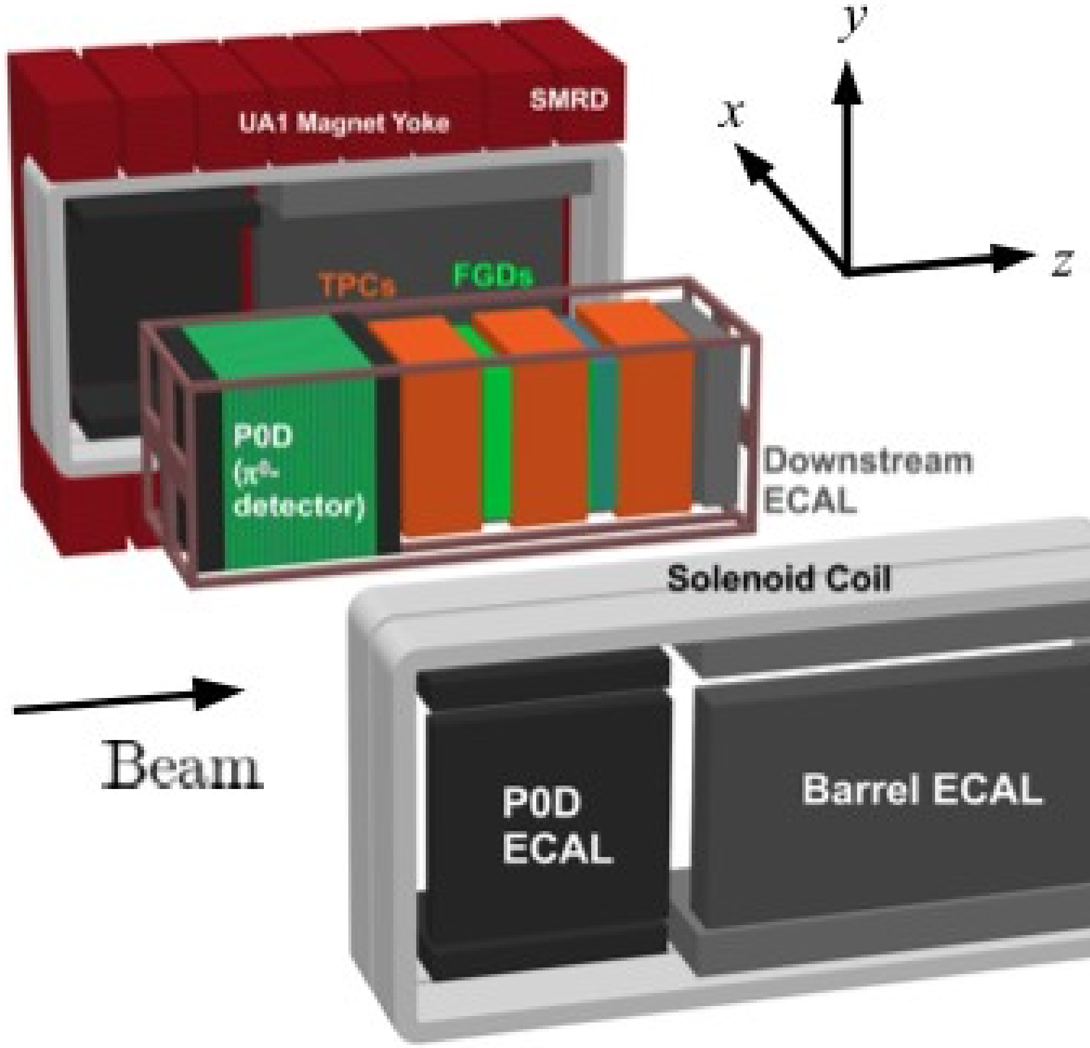
EHDNC: 46.99 GeV

PLACE: 60

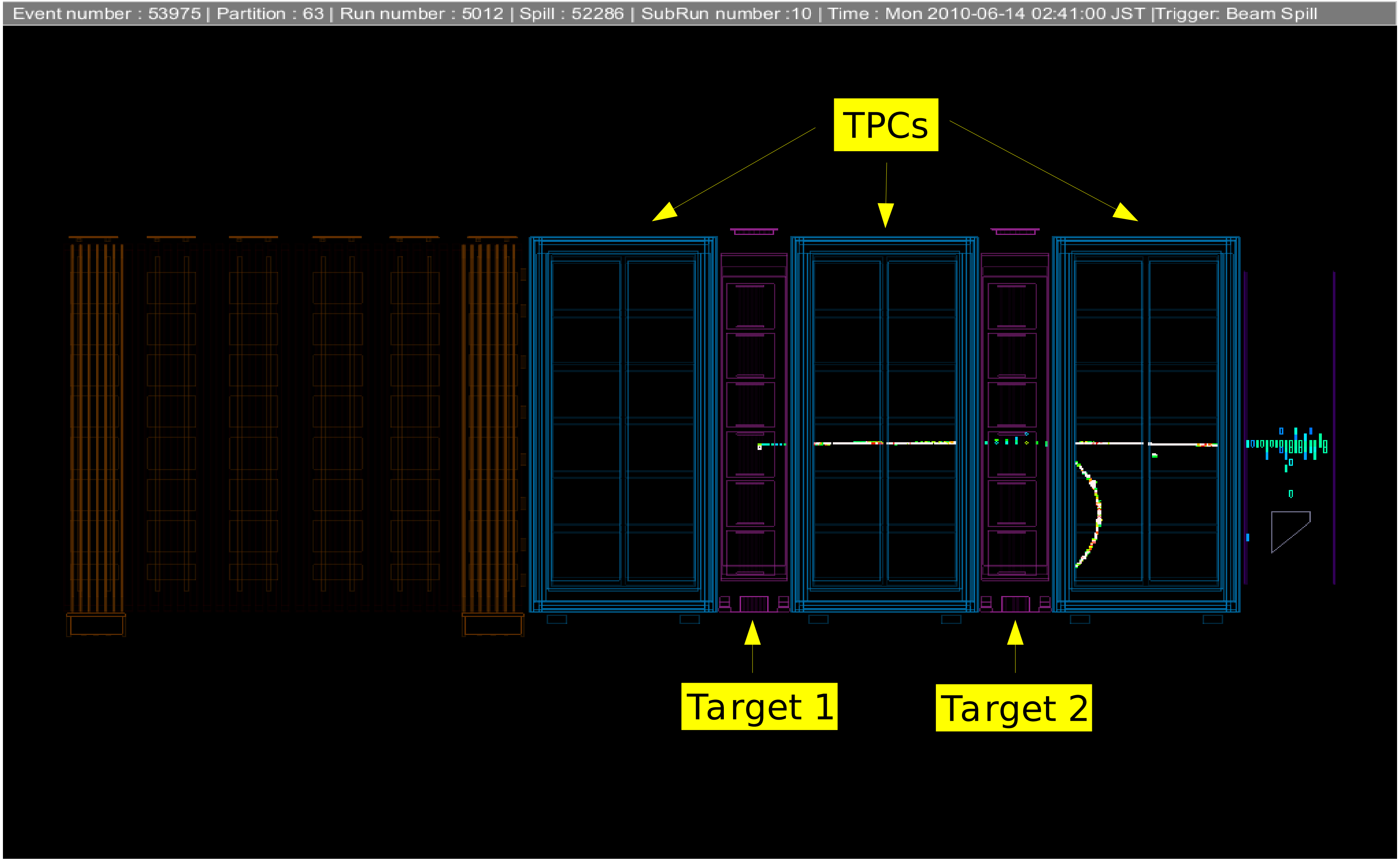
CEXIT: 1

SHEND: 50

T2K ND280


UA1 Magnet Yoke
SMRD
TPCs
FGDs
P0D
(π0-
detector)
Downstream
ECAL
Solenoid Coil
P0D
ECAL
Barrel ECAL
Beam
y
x
z

T2K



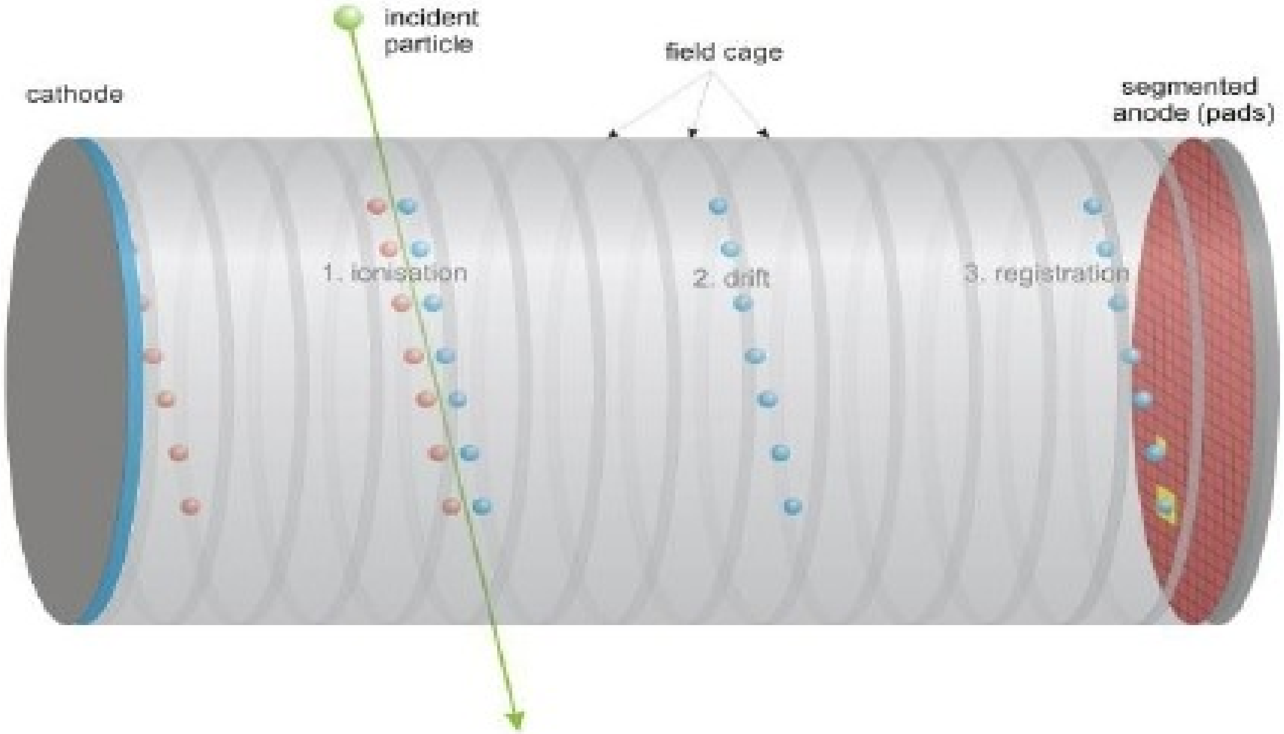
Event number : 53975 | Partition : 63 | Run number : 5012 | Spill : 52286 | SubRun number :10 | Time : Mon 2010-06-14 02:41:00 JST |Trigger: Beam Spill

TPCs

Target 1

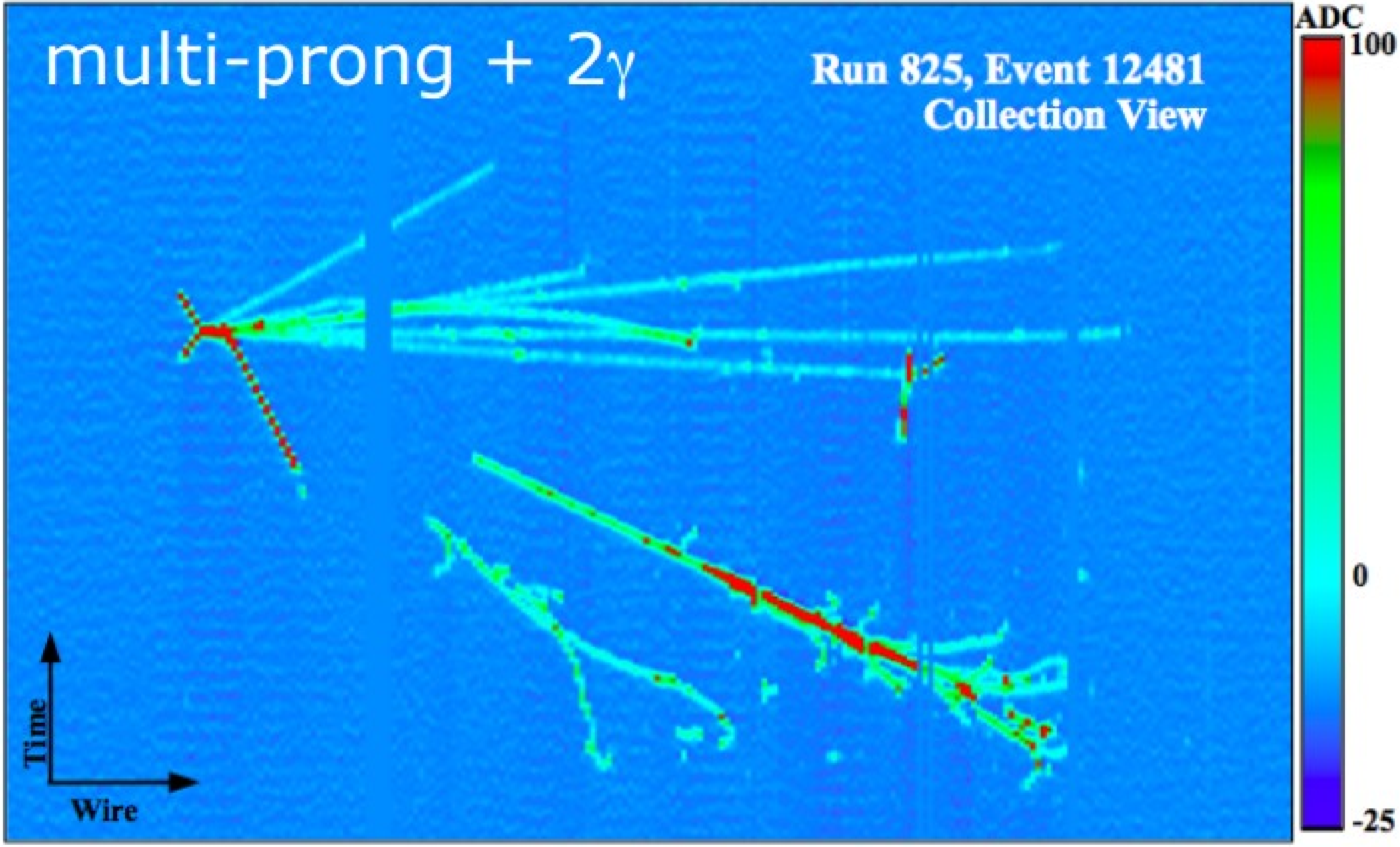
Target 2

Liquid Argon TPCs

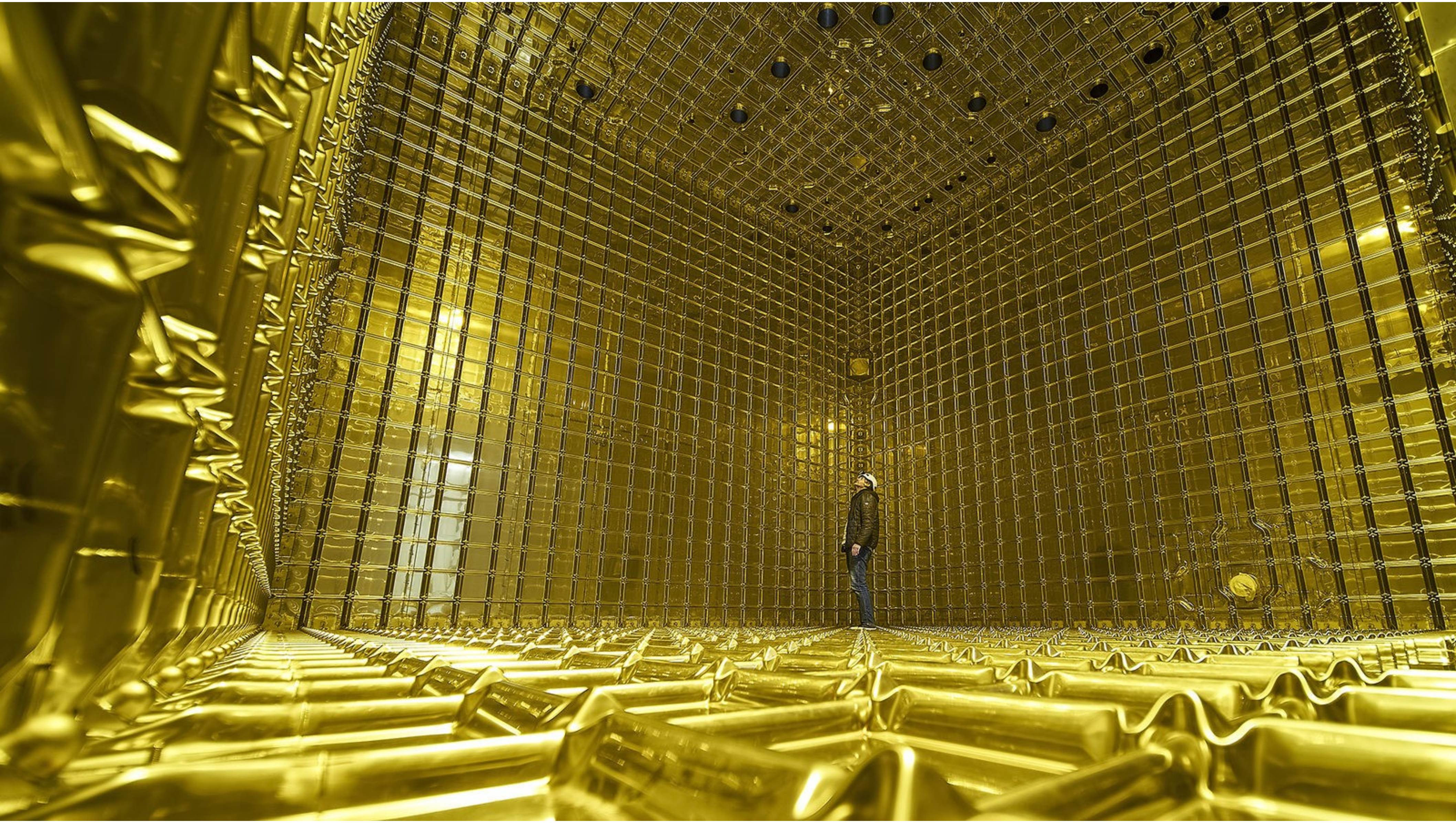


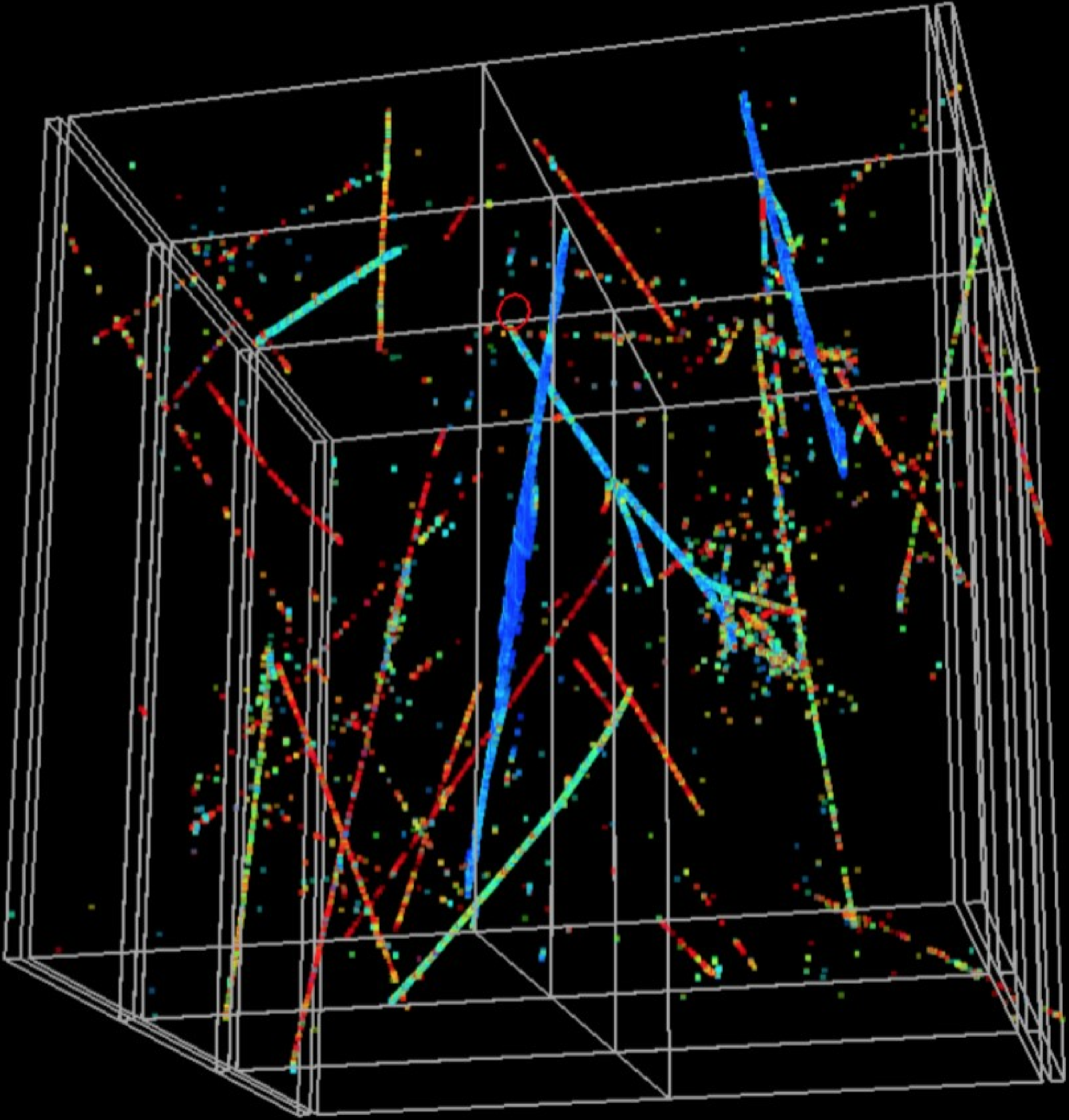
3D tracking with excellent resolution
Calorimetry from energy deposition in filler material
Filler can be gas or liquid.
Neutrino Physics looking at liquid argon TPCs

LAr event


multi-prong + 2γ
Run 825, Event 12481
Collection View
ADC
100
0
-25
Time
Wire

protoDUNE





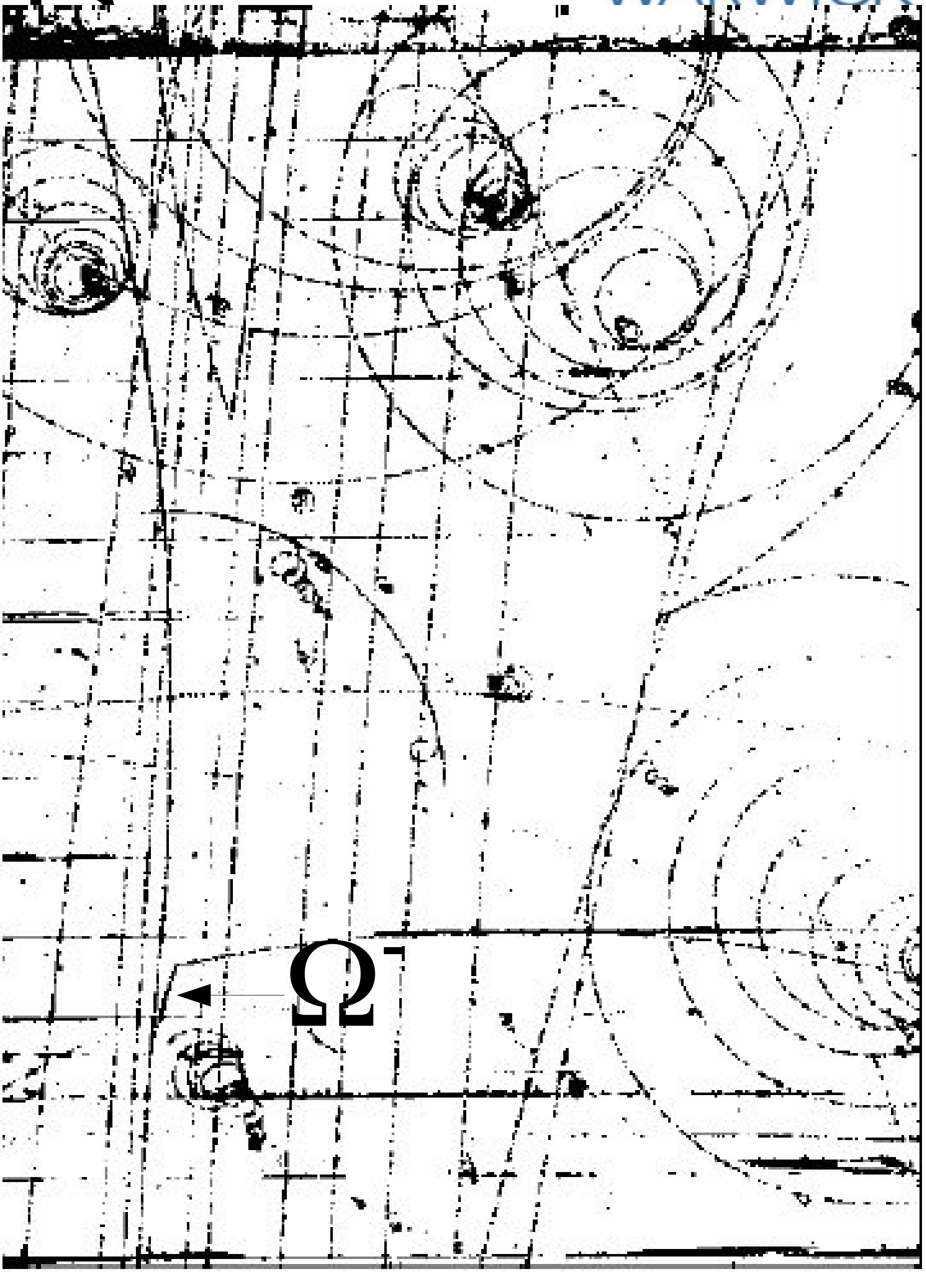
Summary

- 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)

Tracking Chambers

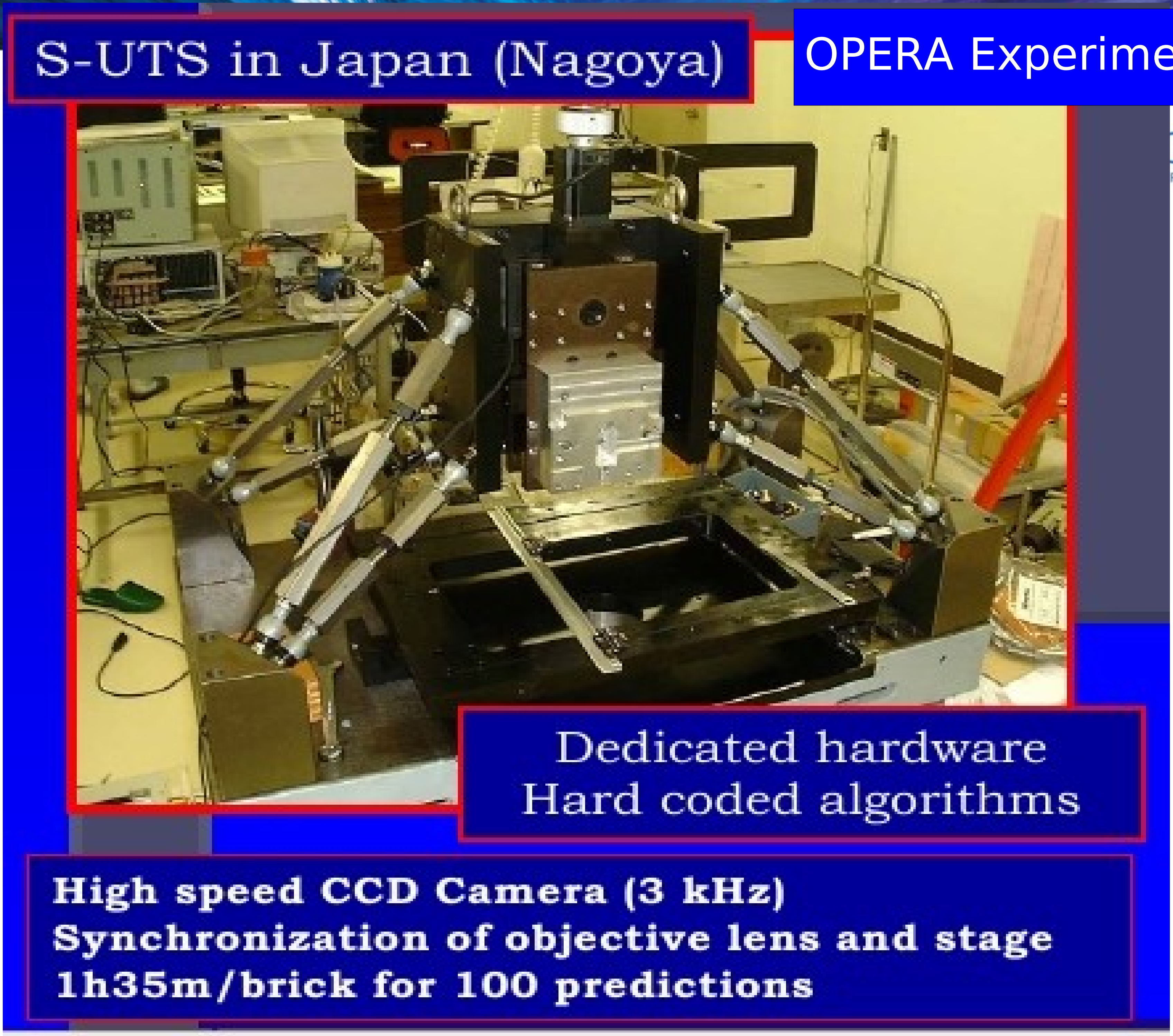

Photo: CERN

BEBC Chamber



The LBL Frankenstein

OPERA Experiment



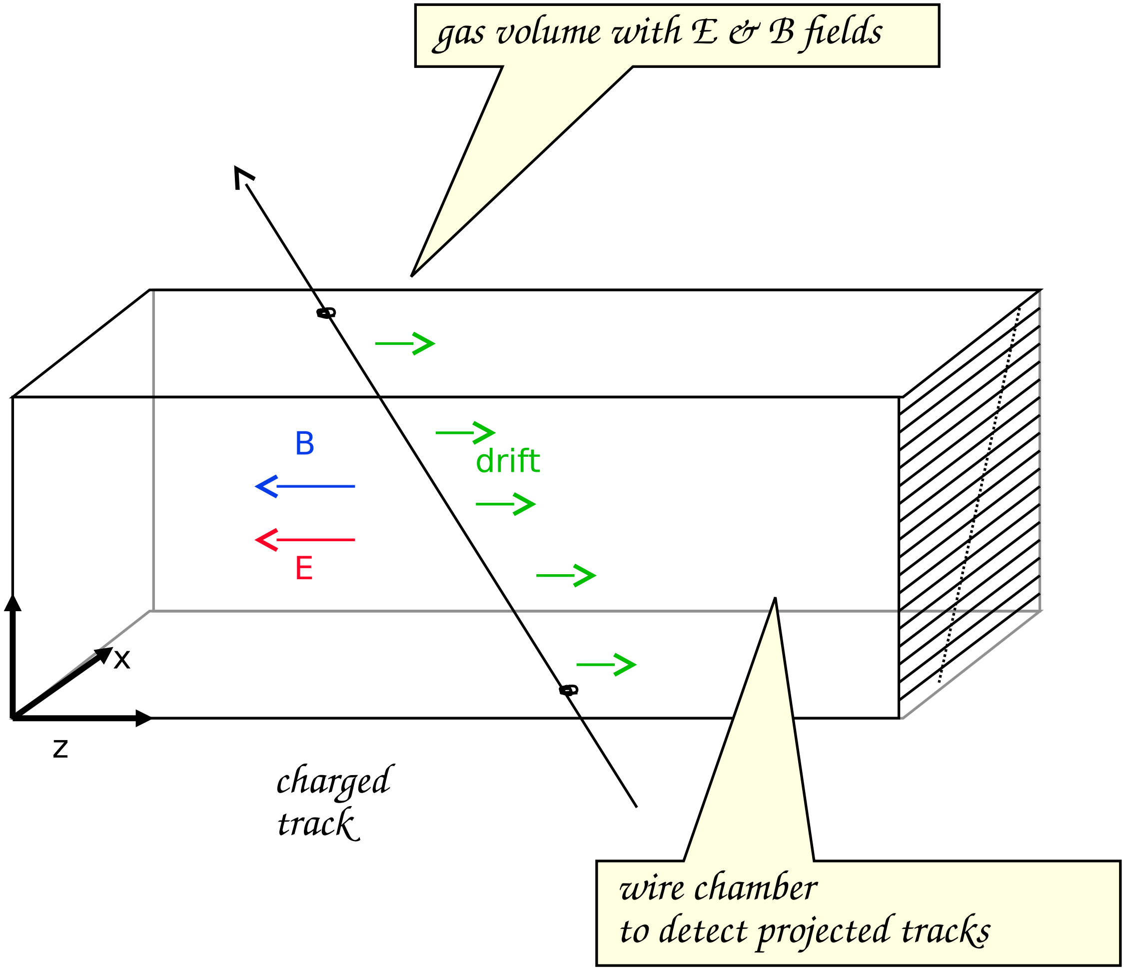
S-UTS in Japan (Nagoya)

Dedicated hardware
Hard coded algorithms

High speed CCD Camera (3 kHz)
Synchronization of objective lens and stage
1h35m/brick for 100 predictions

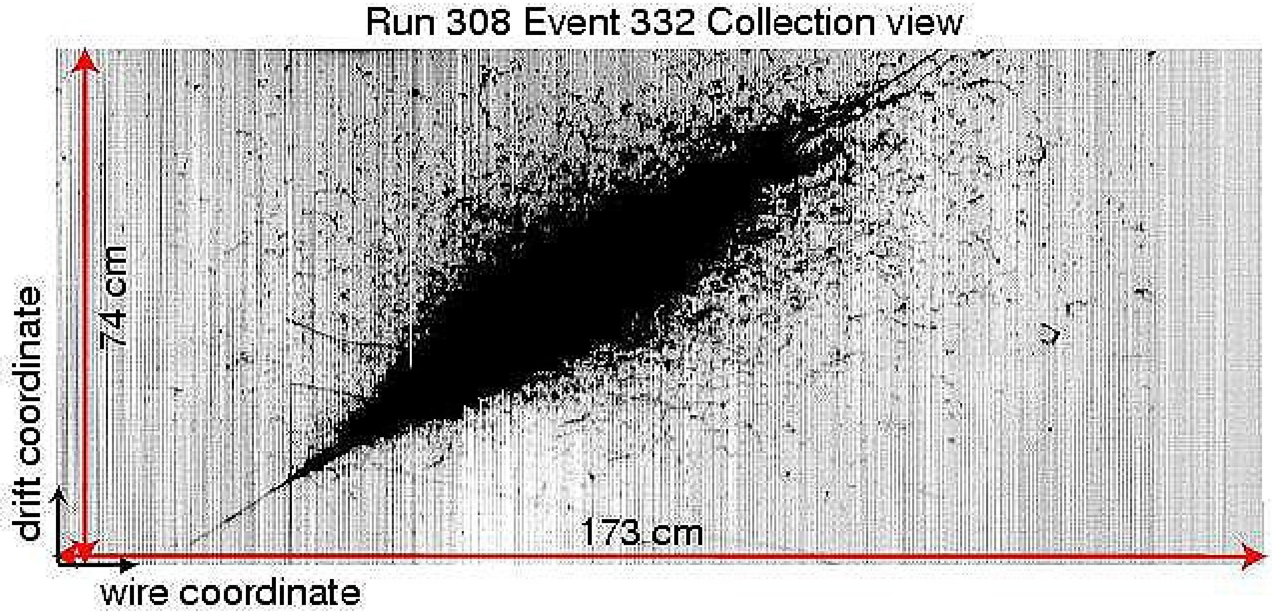
Liquid Argon TPCs

Huge liquid argon TPC. Bubble chamber like imagery and fully active calorimetry

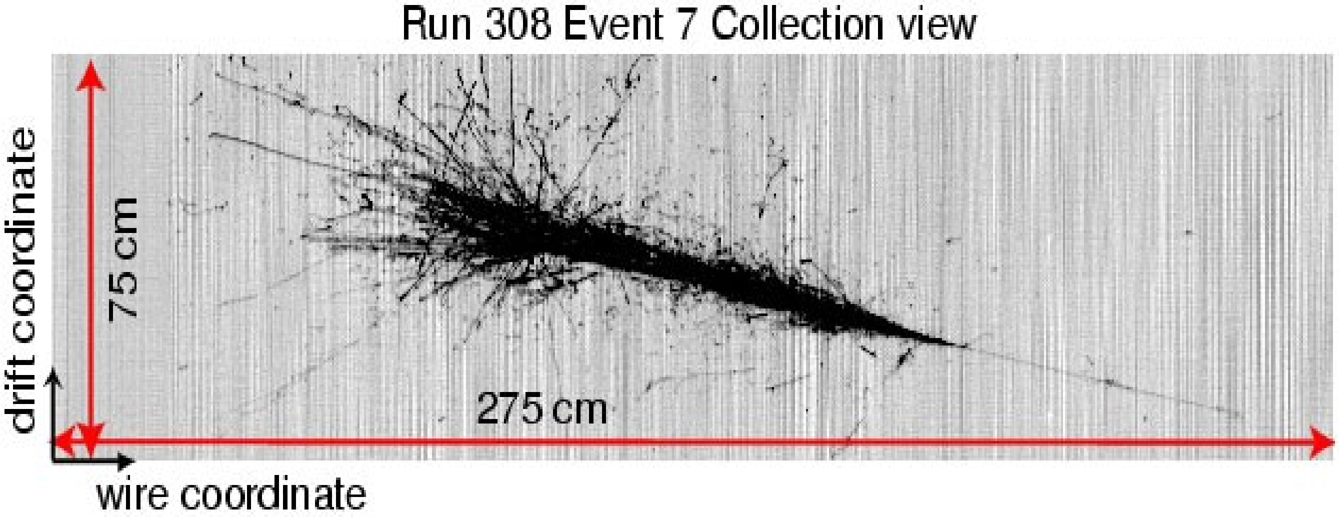


gas volume with E & B fields

wire chamber to detect projected tracks



EM Shower



Hadronoic Shower

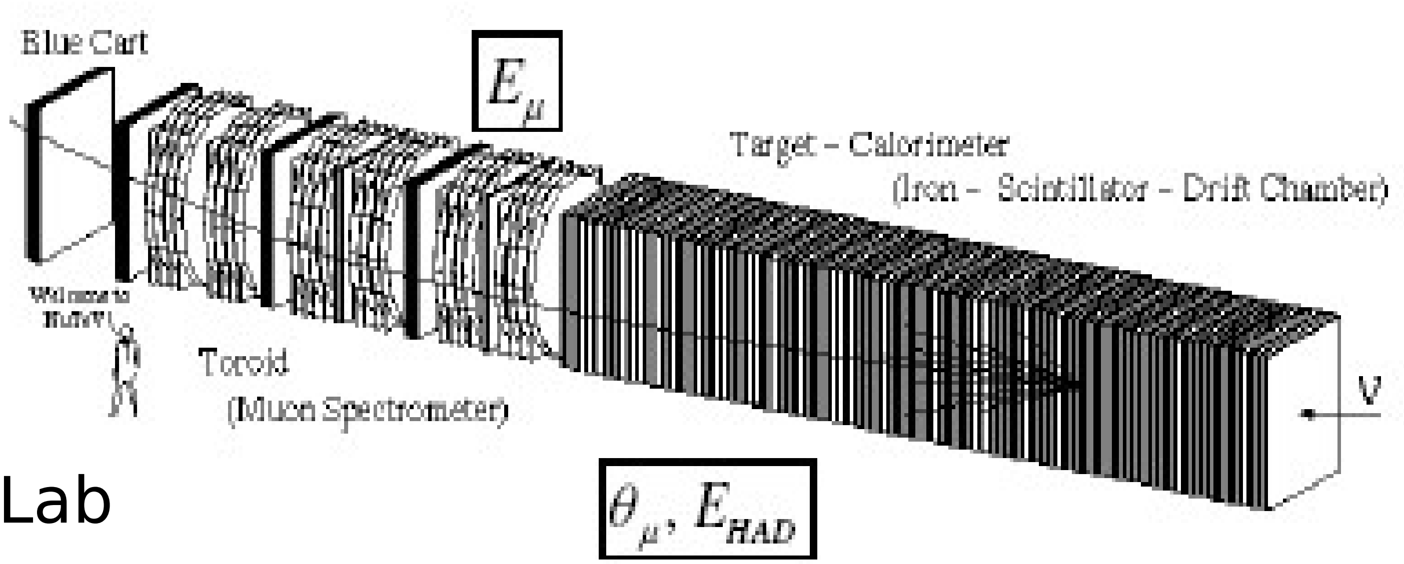
Neutrino Detectors

- No neutrino colliders – detector IS the target
- Low cross section implies large mass
- Neutrinos interact everywhere – vertex can be anywhere
- Identification of charge lepton to separate NC and CC
- Measurement of energy and scattering angle of charged lepton
- Measurement of total hadronic energy
- Identification of single hadrons for hadronic studies
- Use of different target materials (nuclear effects)

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

NUTEV

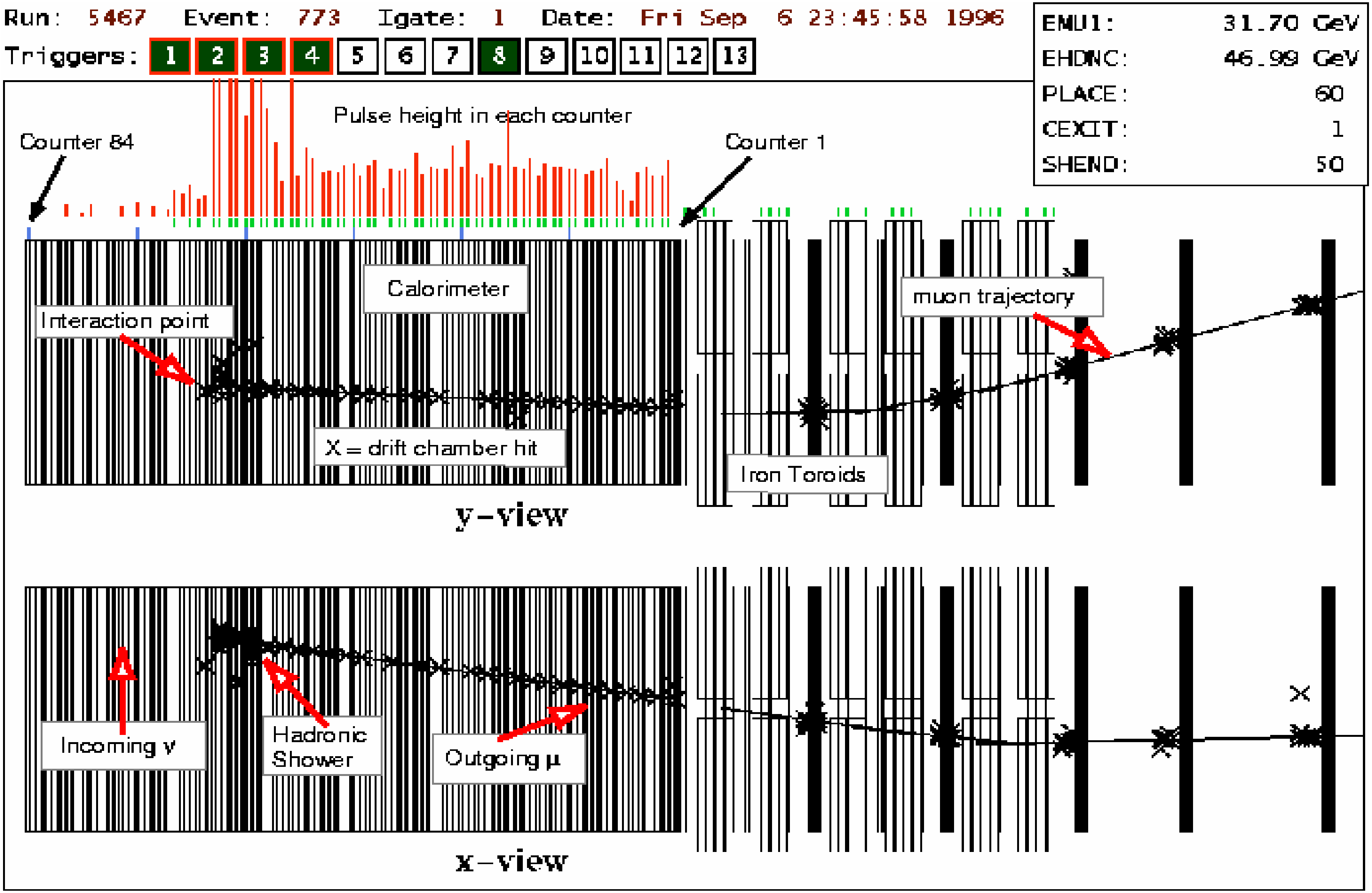
Iron Sampling calorimeter : CDHS,CHARM,CCFR,NUTEV,MINOS



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 Event Display



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

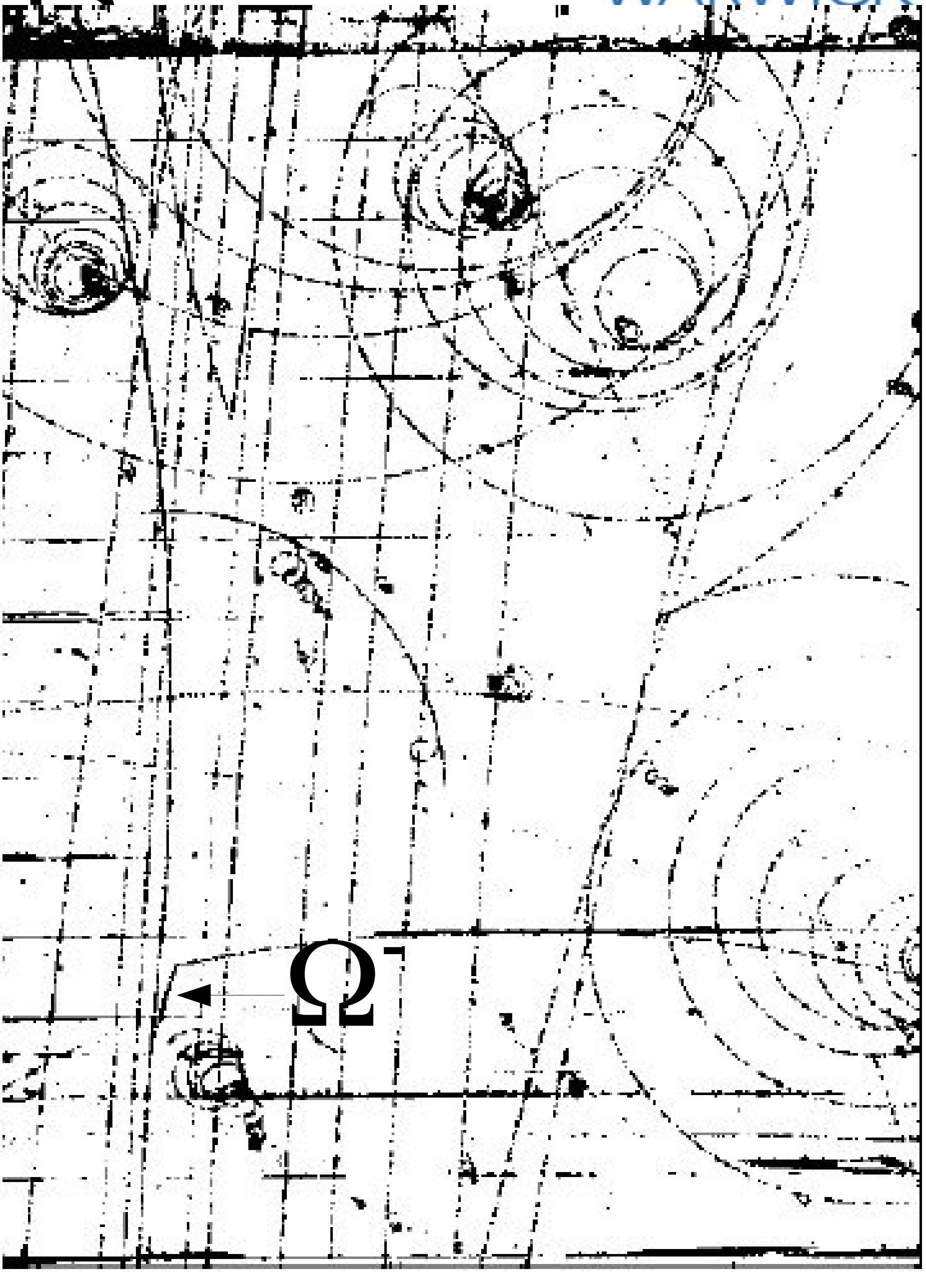
Triggers: 1 2 3 4 5 6 7 8 9 10 11 12 13

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

Tracking Chambers


Photo: CERN

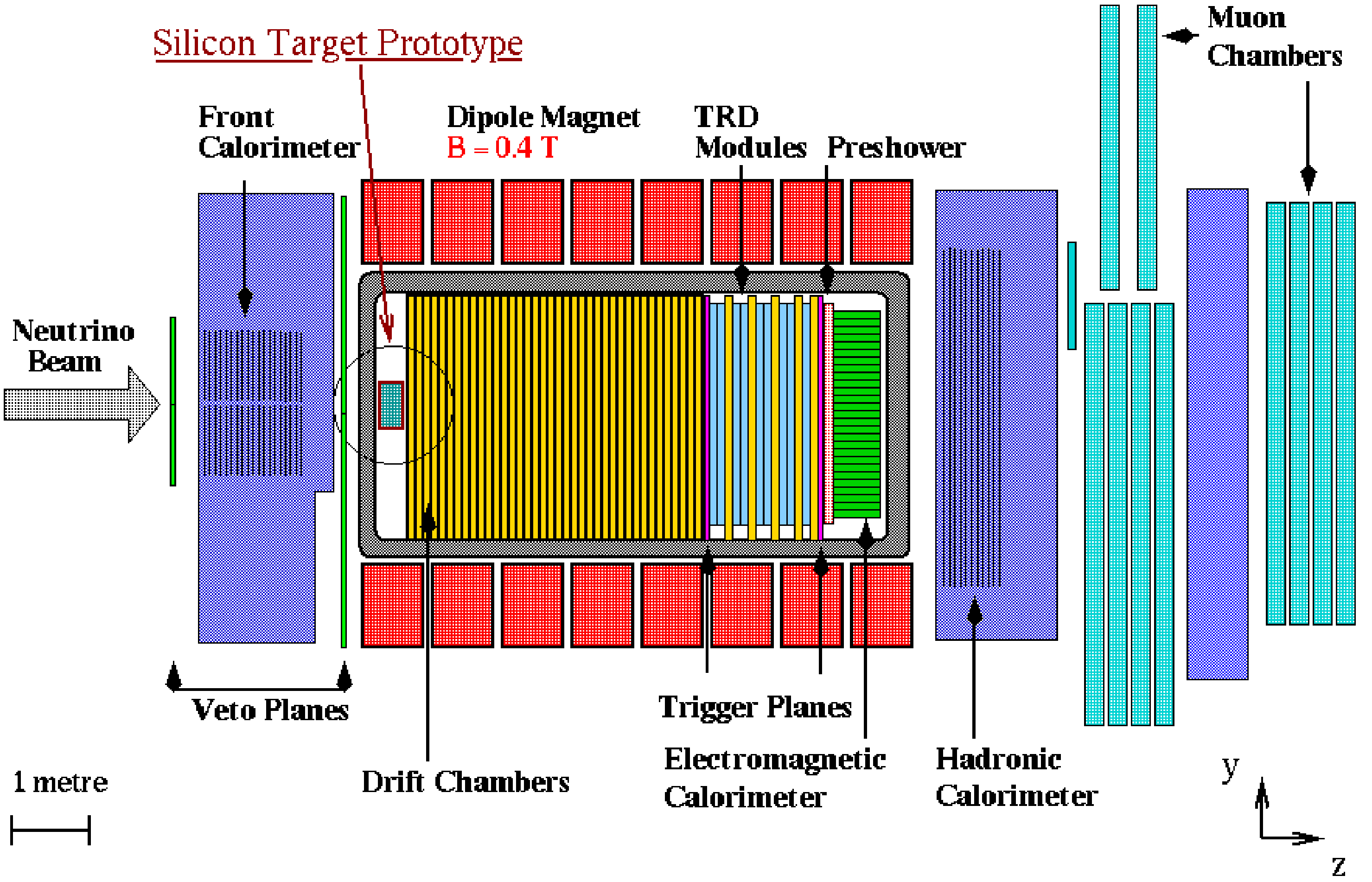
BEBC Chamber



NOMAD

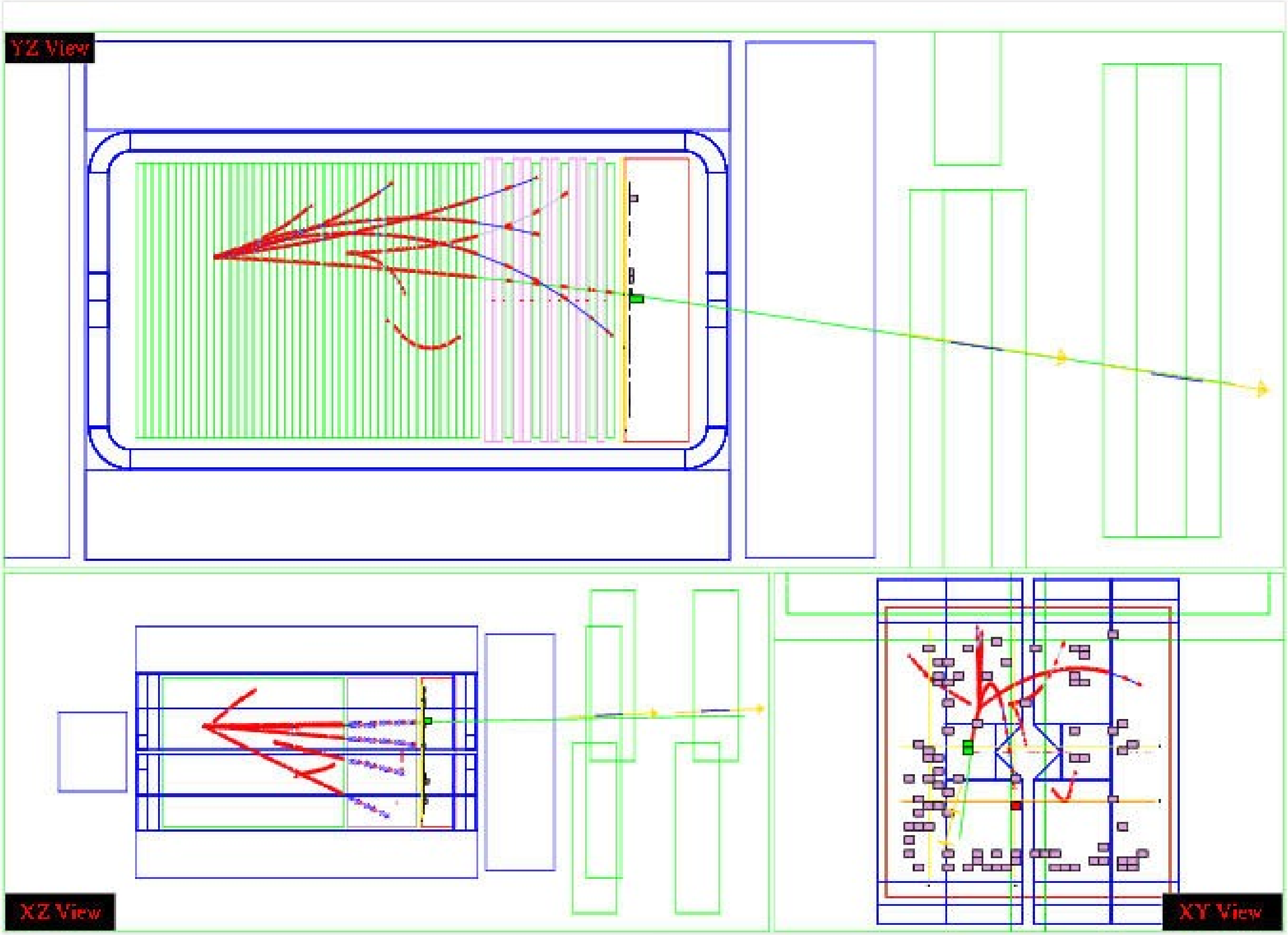
Electronic tracking : NOMAD,CHORUS,BEBC,ICARUS

CERN



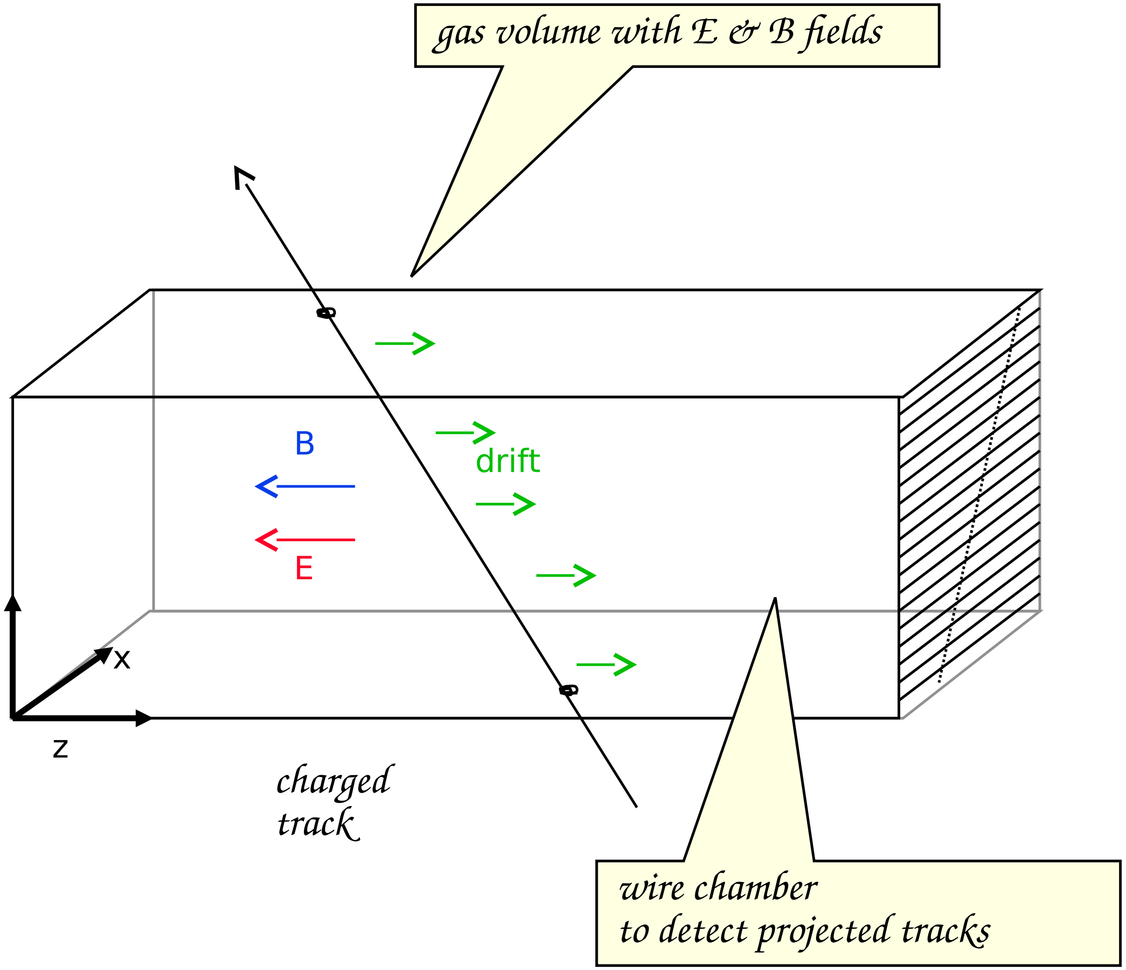
Target was a set of drift chambers with inset carbon planes

NOMAD Event Display

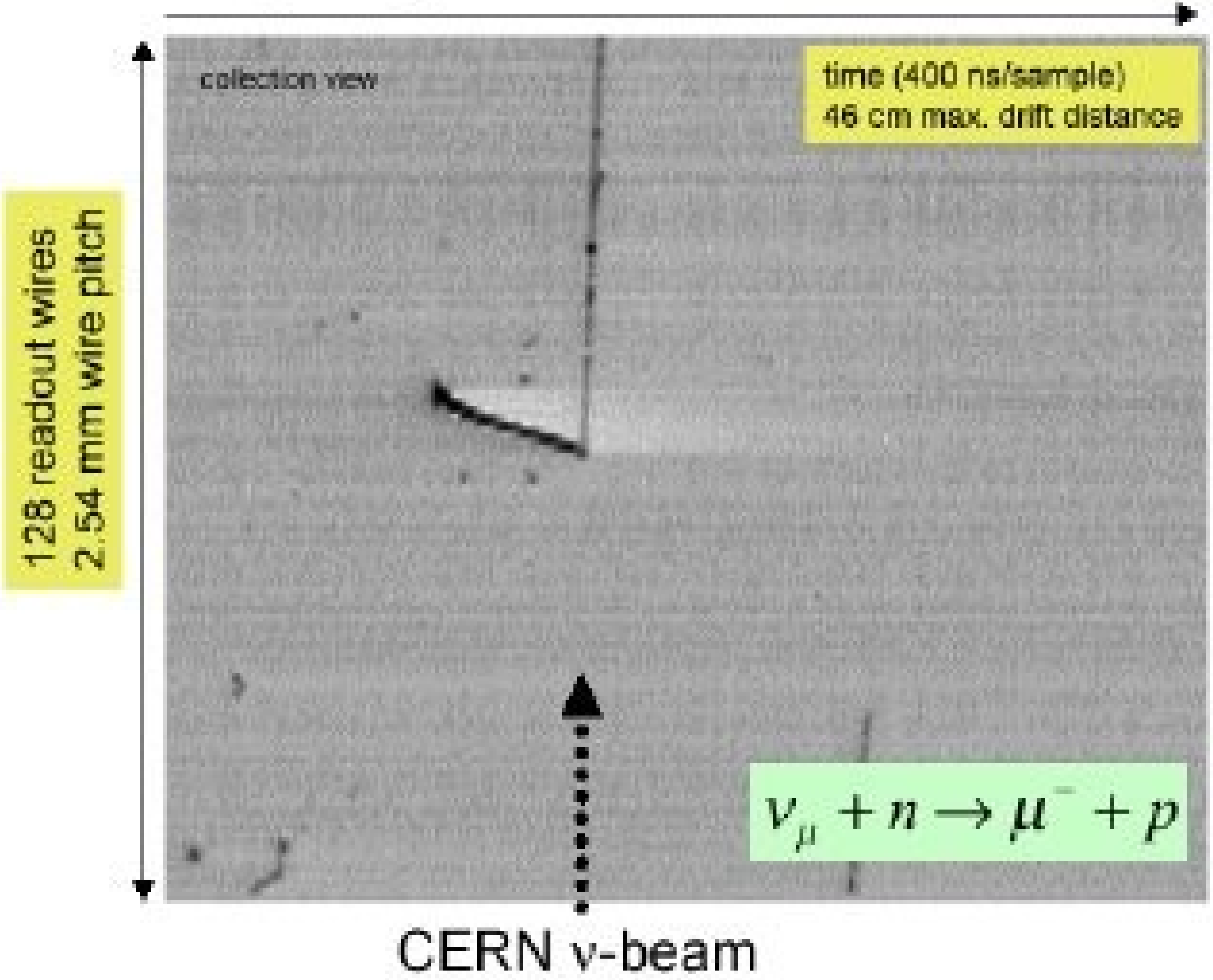


ICARUS

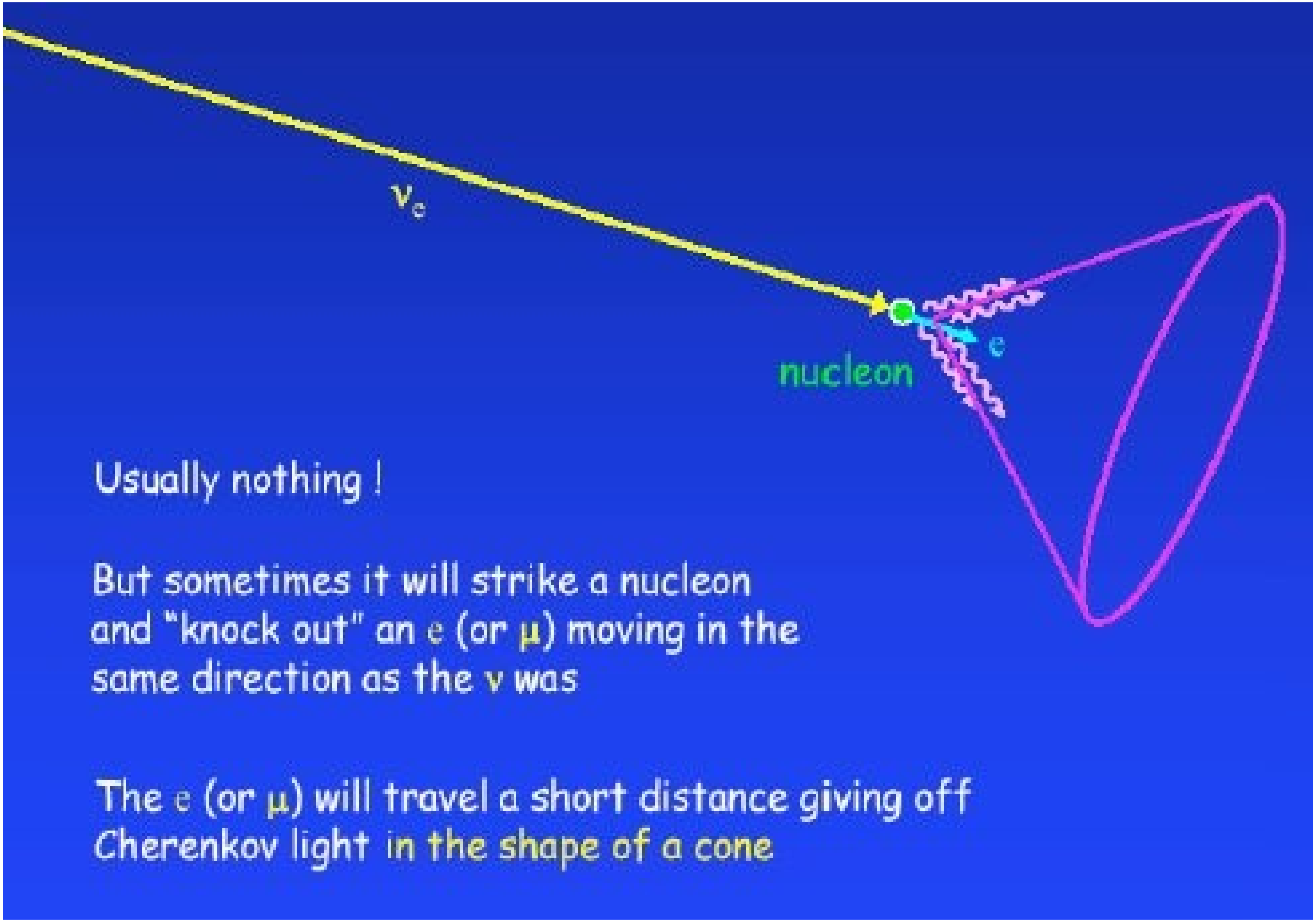
Huge liquid argon TPC. Bubble chamber like imagery and fully active calorimetry



ICARUS


collection view
time (400 ns/sample)
46 cm max. drift distance
128 readout wires
2.54 mm wire pitch
$\nu_\mu + n \rightarrow \mu^- + p$
CERN ν-beam

Water Cerenkov



Usually nothing !

But sometimes it will strike a nucleon and "knock out" an e (or μ) moving in the same direction as the ν was

The e (or μ) will travel a short distance giving off Cherenkov light in the shape of a cone

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

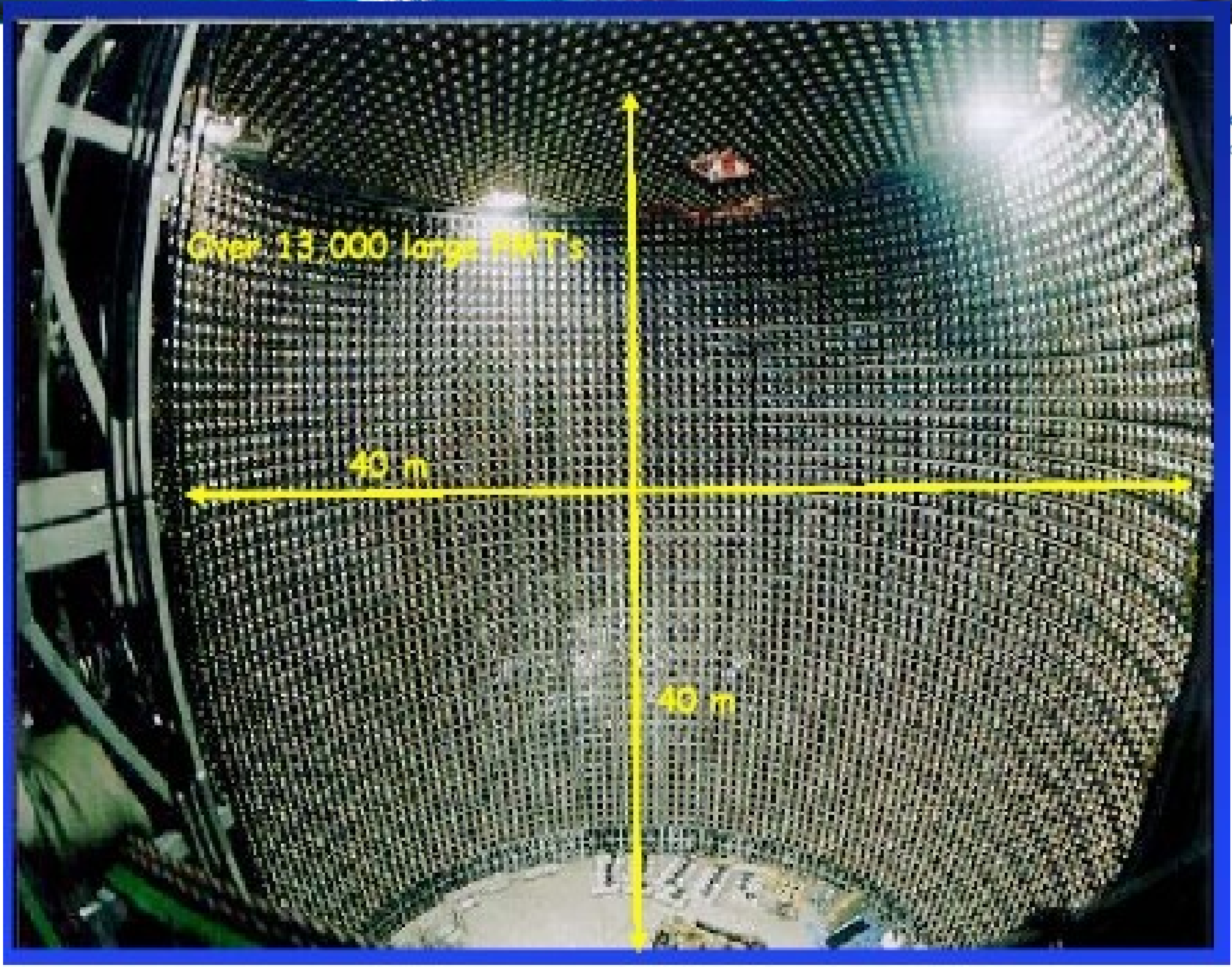
Super-Kamiokande

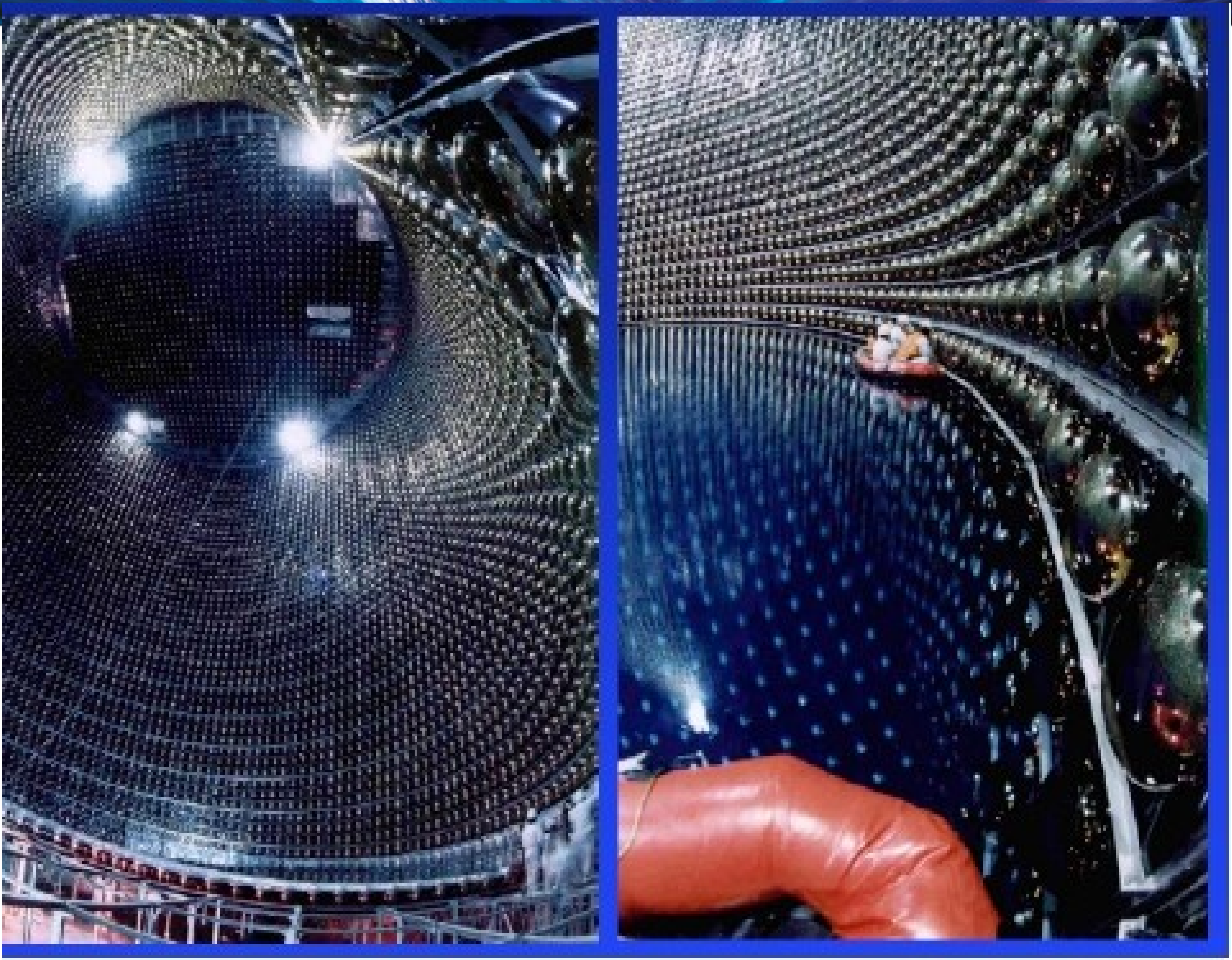
Super-Kamiokande

SK-1 1996 - 2001
- 22.5 kton fiducial mass (2m from wall)
- 11146 50-cm photomultiplier tubes
- 40% photocathode coverage
- 1885 20-cm pmts in outer detector

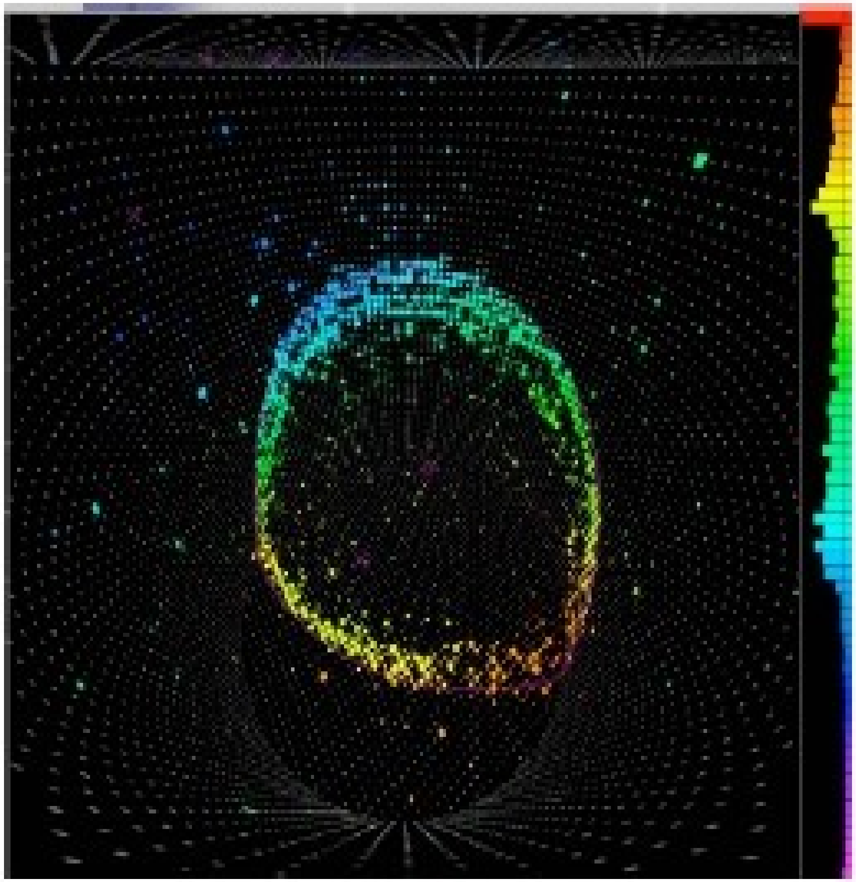
SK-2 January 2003 - October 2005
- 5182 PMTs, mostly recovered from accident
- ~19% coverage with acrylic shields →
- outer detector fully restored
- K2K beam resumed

SK-3 March 2006 +
- original coverage to be restored
- T2K off-axis beam from J-PARC

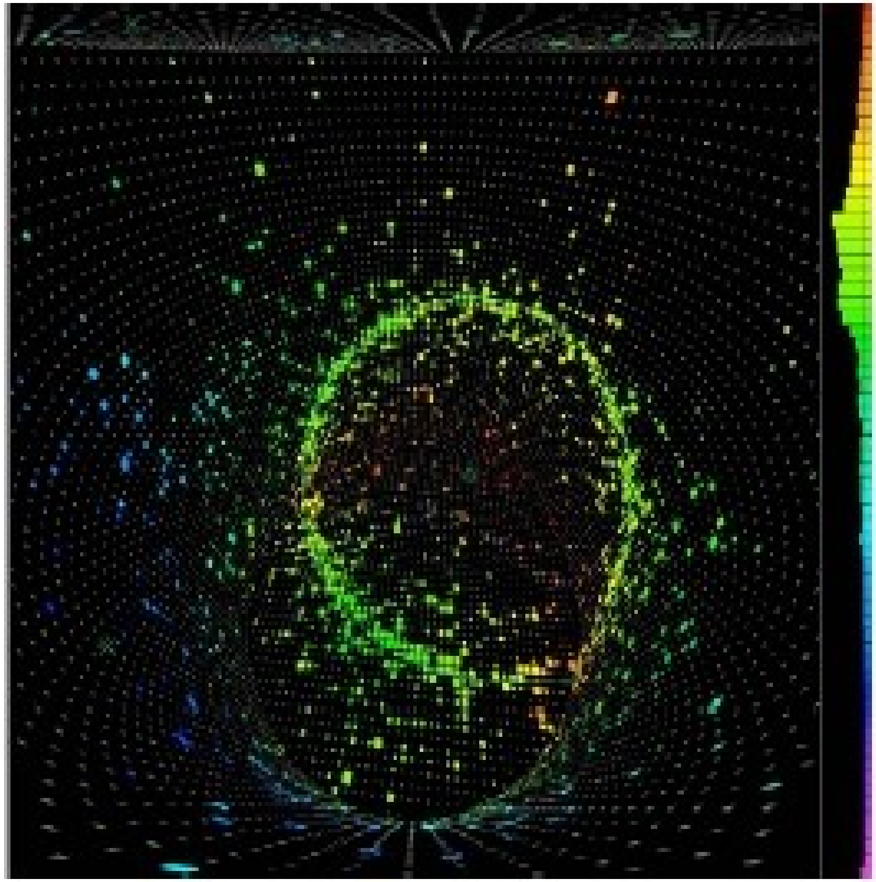

Over 13,000 large PMT's
40 m
40 m



Example



Stopping muon

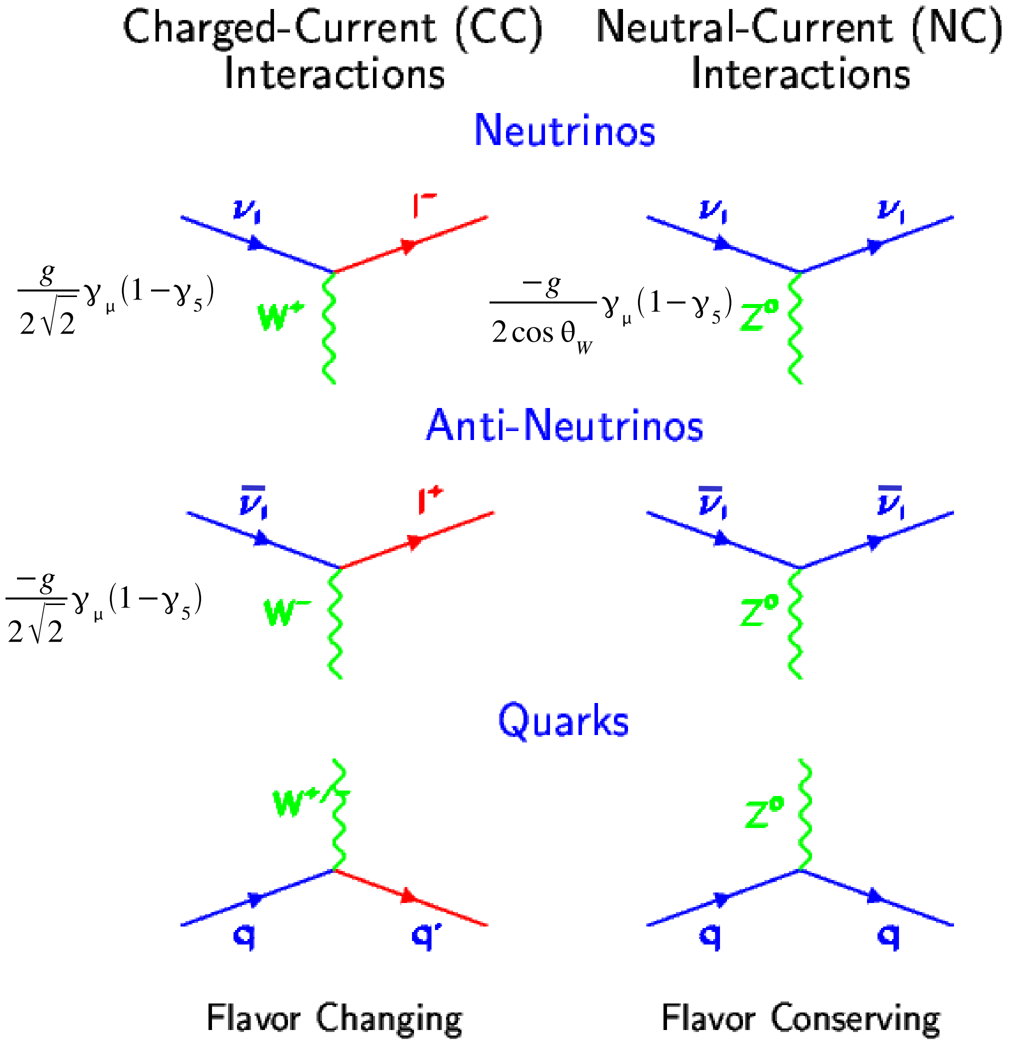


Electron

Neutrino Interactions

In which neutrinos interact elastically, semi-elastically and inelastically

Neutrinos in the Standard Model



$$\frac{g}{2\sqrt{2}}\gamma_\mu(1-\gamma_5)$$

$$\frac{-g}{2\cos\theta_W}\gamma_\mu(1-\gamma_5)$$

$$\frac{-g}{2\sqrt{2}}\gamma_\mu(1-\gamma_5)$$

W exchange gives CC
Z exchange gives NC

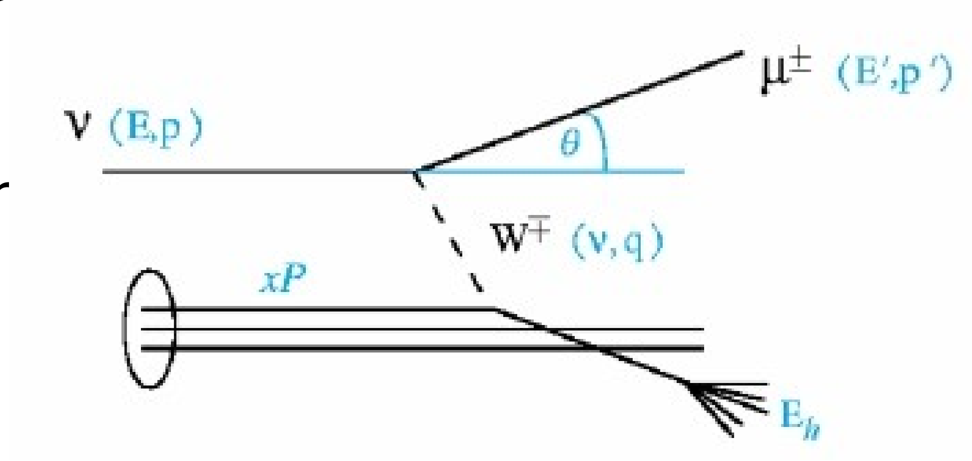
In CC the flavour of the outgoing lepton determines flavour of neutrino; charge of lepton determines if neutrino or antineutrino

Neutrinos are special in the Standard Model – only fermion that couples only to the weak current

Z0 also couples to right handed (chiral) singlets

Scattering Variables

Most interactions described in terms of scattering variables based on Lorentz invariants



E', θ, E_h are measured

$$4-Momentum\ transfer^2: Q^2=-q^2=-(p-p')^2\approx(4E'E\sin^2\theta/2)_{lab}$$

$$Energy\ transfer: \nu=(q\cdot P)/M_T=(E-E')_{lab}=(E_h-M_T)_{lab}$$

$$Inelasticity: y=(q\cdot P)/(p\cdot P)=(E_h-M_T)_{lab}/(E_h+E')_{lab}$$

$$Bjorken\ scaling\ variable\ x=Q^2/2M_T\nu$$

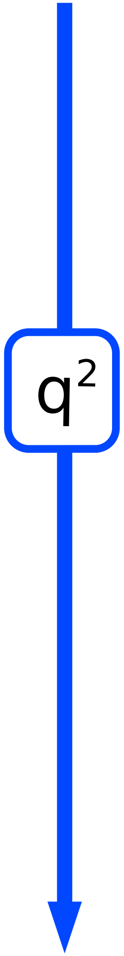
$$Recoil\ Mass^2: W^2=(q+P)^2=M_T^2+2M_T\nu-Q^2$$

$$CM\ Energy: s=(p+P)^2=M_T^2+Q^2/xy$$

Neutrino-Nucleon Interactions in a Nutshell

CC – $W^{\pm}$ exchange

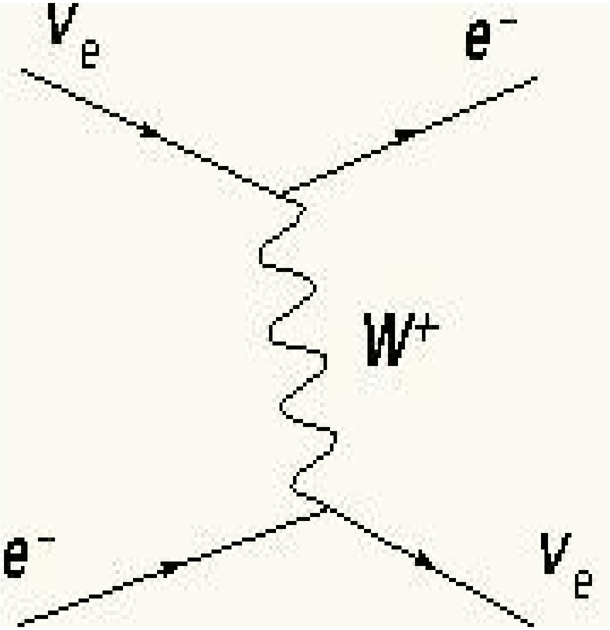
- Quasi-elastic Scattering
  Target changes but no breakup
  $\nu_\mu + n \rightarrow \mu^- + p$
- Coherent/Diffractive production
  Target unchanged
  $\nu_\mu + n \rightarrow \mu^- + n + \pi^+$
- Nuclear resonance production
  Target goes to excited state and decays
  $\nu_\mu + n \rightarrow \mu^-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


q^2

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
  ν_μ + quark $\rightarrow \nu_\mu$ + quark

Neutrino Electron CC Scattering



$$L=\frac{G_F}{\sqrt{2}}[\overline{\nu}_e\gamma^\mu(1-\gamma_5)e][\overline{\mu}\gamma_\mu(1-\gamma_5)\nu_\mu]$$

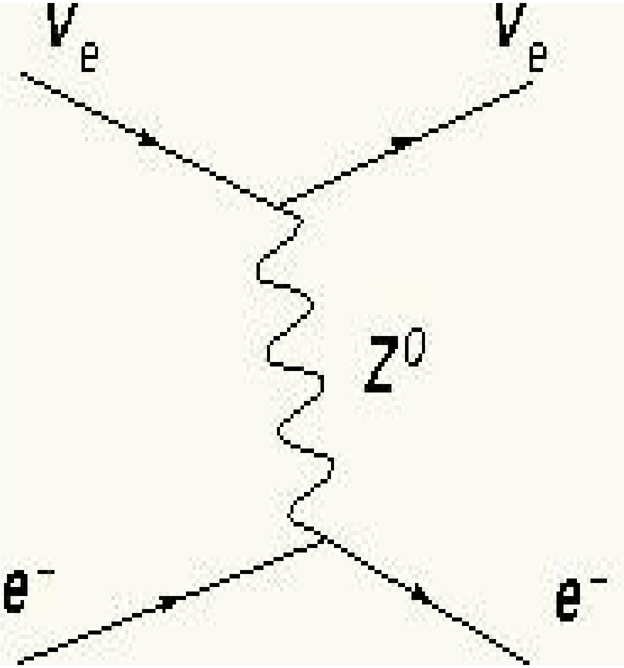
$$\frac{d\sigma_{CC}(\nu_\mu e)}{dy}=\frac{G_F^2 s}{\pi}\frac{M_W^2}{q^2-M_W^2}\sim\frac{G_F^2 s}{\pi}$$

$$\boxed{\sigma_{CC}(\nu_\mu e)=\frac{G_F^2 s}{\pi}=1.7\times10^{-41}\left(\frac{E_\nu}{1GeV}\right)cm^2}$$

NB Neutrino always couples to the negative charged lepton

- proportional to Eν
- General property of a point interaction with no structure
- V-A at both vertices

Neutrino Electron NC Scattering



$$L=\frac{G_F}{\sqrt{2}}[\overline{\nu_\mu}\gamma^\mu(1-\gamma_5)\nu_\mu][\bar{e}\gamma_\mu(g_V-g_A\gamma_5)e]$$

mixture

$$g_L\bar{e}\gamma_\mu(1-\gamma_5)e+g_R\bar{e}\gamma_\mu(1+\gamma_5)e$$

Left handed   Right handed

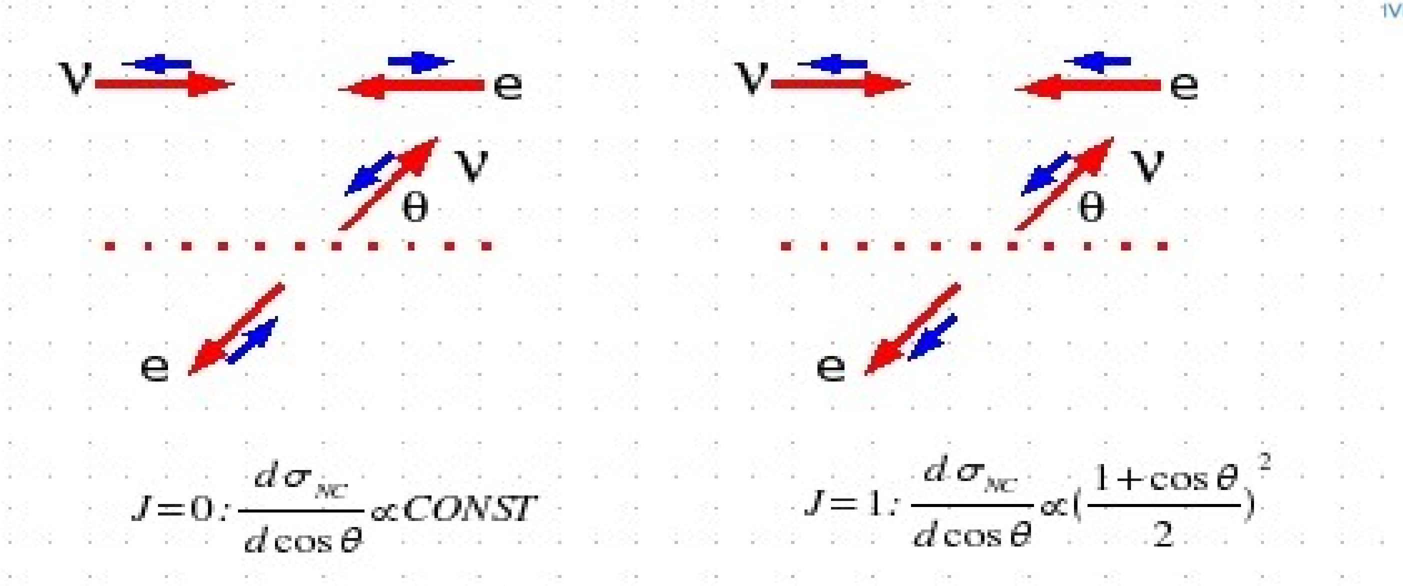
$$g_L=\frac{1}{2}(g_V+g_A)=-\frac{1}{2}+\boxed{\sin^2\theta_W}\quad g_R=\frac{1}{2}(g_V-g_A)=\sin^2\theta_W$$

$$\frac{d\sigma_{NC}(\nu_\mu e)}{dy}=\frac{G_F^2 s}{\pi}\frac{m_Z^2}{q^2-m_Z^2}[g_L^2+g_R^2(1-y)^2]$$

$$\frac{d\sigma_{NC}(\overline{\nu_\mu} e)}{dy}=\frac{G_F^2 s}{\pi}\frac{m_Z^2}{q^2-m_Z^2}[g_L^2(1-y)^2+g_R^2]$$

Z^0 can couple right handed fermion singlets as well.

Angular spectra



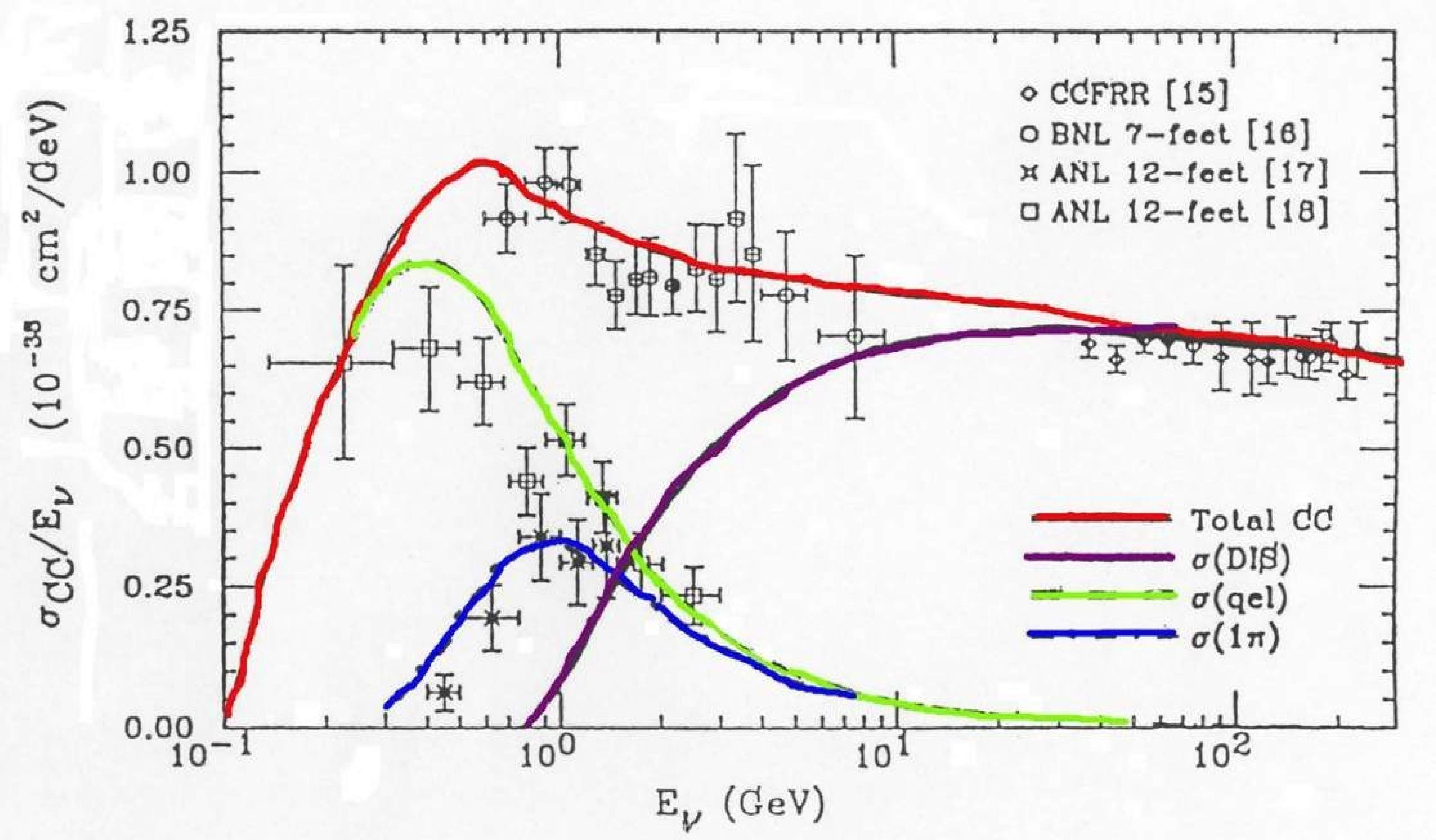
Isotropic

No back scattering
Helicity mismatch

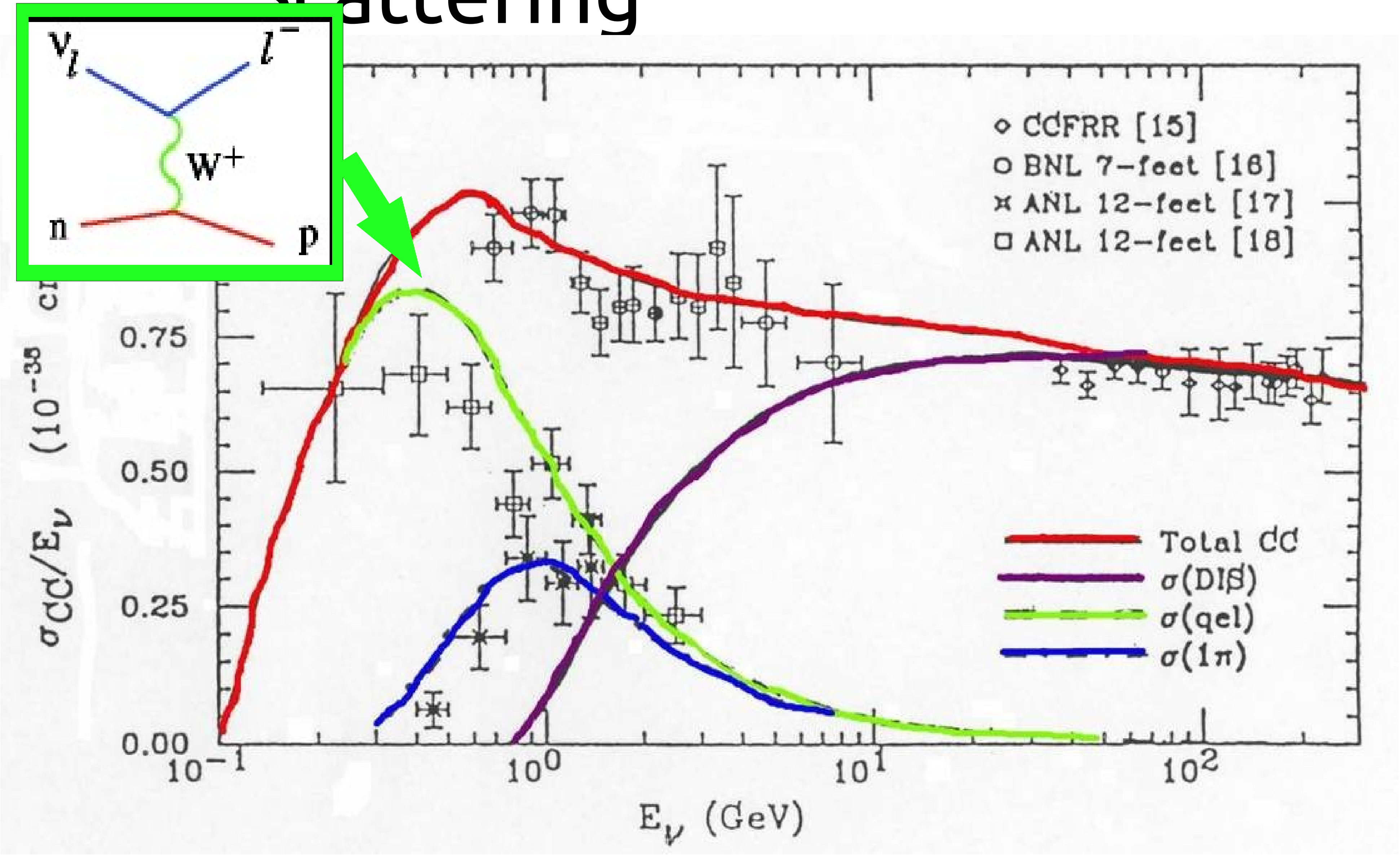
$$\frac{d\sigma_{NC}(\nu_\mu e)}{dy} \sim [g_L^2 + g_R^2(1-y)^2]$$

Y=0 ⇒ forward scattering. Both J=0,J=1 can occur
Y=1 ⇒ backward scattering. Only J=0 can happen.

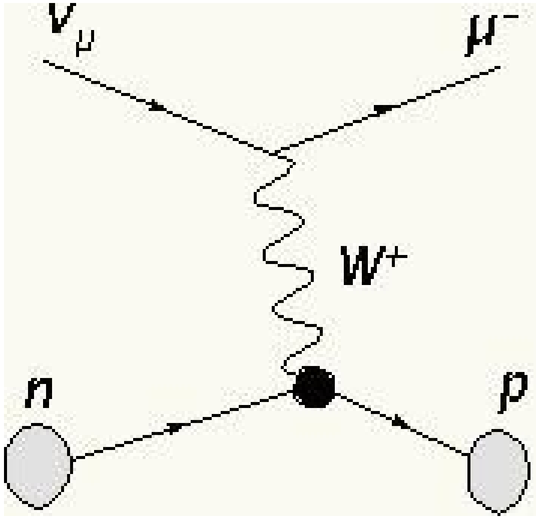
Neutrino cross sections



Quasi-elastic Scattering



Quasi-elastic Scattering



Now we have a complex hadronic target to think about

$$M=\frac{G_F\cos\theta_C}{\sqrt{2}}[\bar{\mu}\gamma_\alpha(1-\gamma_5)\nu]\boxed{[\bar{p}\gamma^\alpha(F_V(Q^2)+F_A(Q^2)\gamma_5)n]}$$

Standard V-A

Vector Form factor

Axial-vector form factor

The form factors must be measured.
Only neutrino interactions can determine F_A.

$$F_{V,A}(Q^2)=\frac{F_{V,A}(0)}{\left(1-\frac{q^2}{M^2_{V,A}}\right)^2}$$

Dipole Approximation

$F_V(0)=1$; $M_V = 0.84$ GeV
$F_A(0)=g_A/g_V=-1.267$
$M_A \approx 1.026 \pm 0.02$

Experimental signature

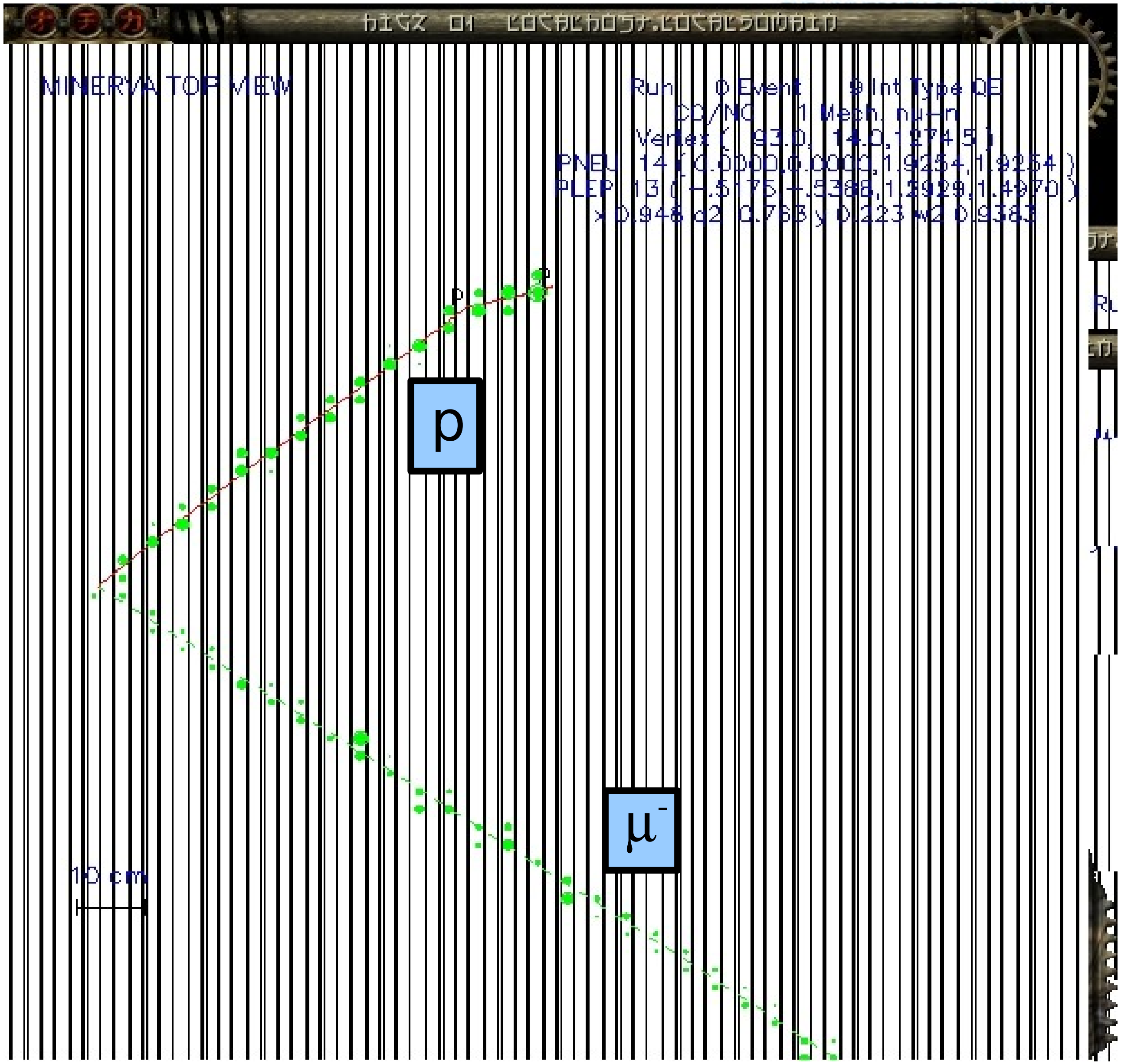
$$\boxed{\nu_\mu + n \to \mu^- + p}$$

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

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

Proton id from dEdx
Muon id from range
Two-body so angles are known if E_μ is known

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



```
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
```

Importance of CC QE

- Absolute neutrino flux is never known to better than 20-30%
- This makes absolute cross sections hard to measure accurately so experimentalists like to measure cross section ratios

$$R=\frac{\sigma_{process}}{\sigma_{norm}}=\frac{N_{process}*\Phi_{\nu}/\epsilon_{process}}{N_{norm}*\Phi_{\nu}/\epsilon_{norm}}$$

- Ideally, want a well known normalisation cross section
- Would be great to use ν-e scattering since the cross section is known to much better than a percent but cross section is too small.
- Next best thing is the CC QE process

Problems with QE

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

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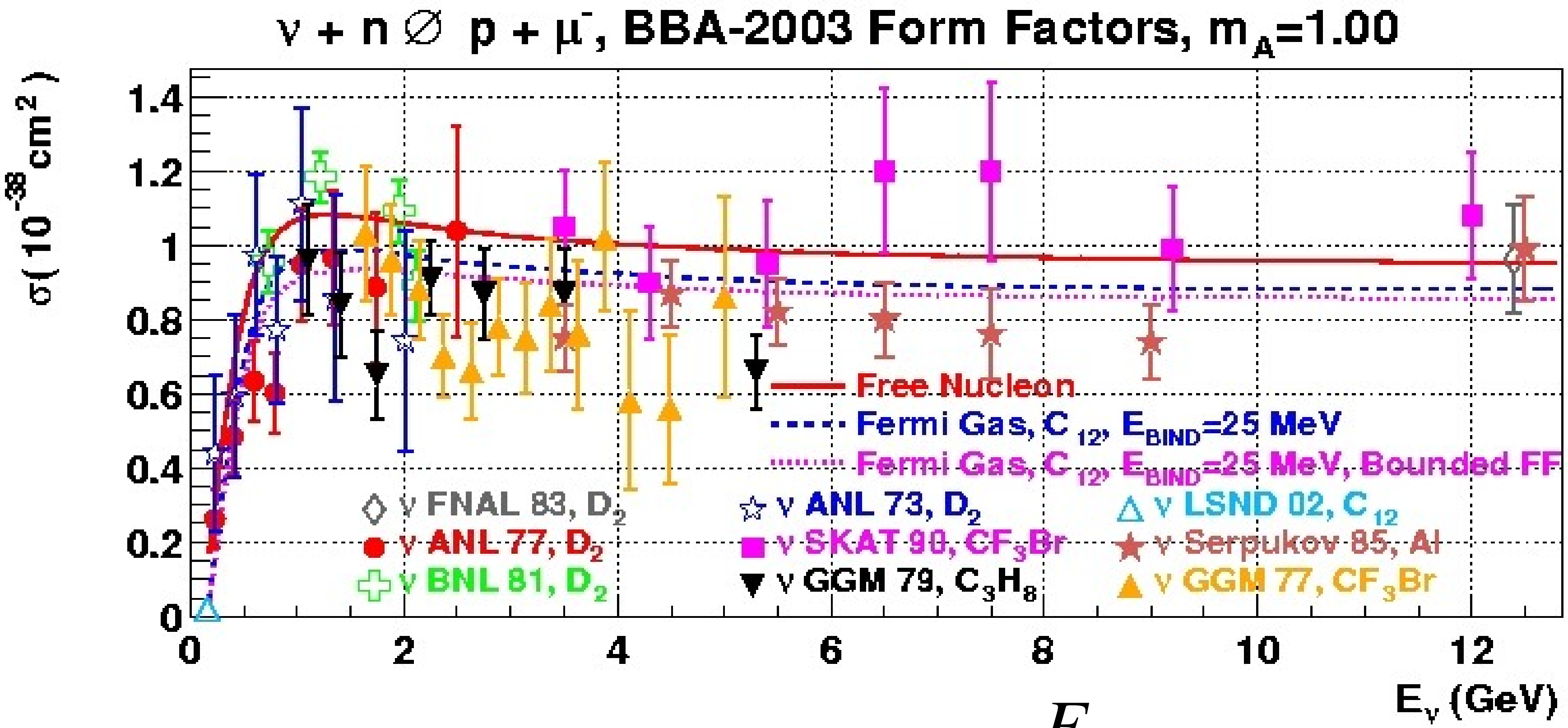
The CC QE process is the best known neutrino process occurring at a few GeV



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

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

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

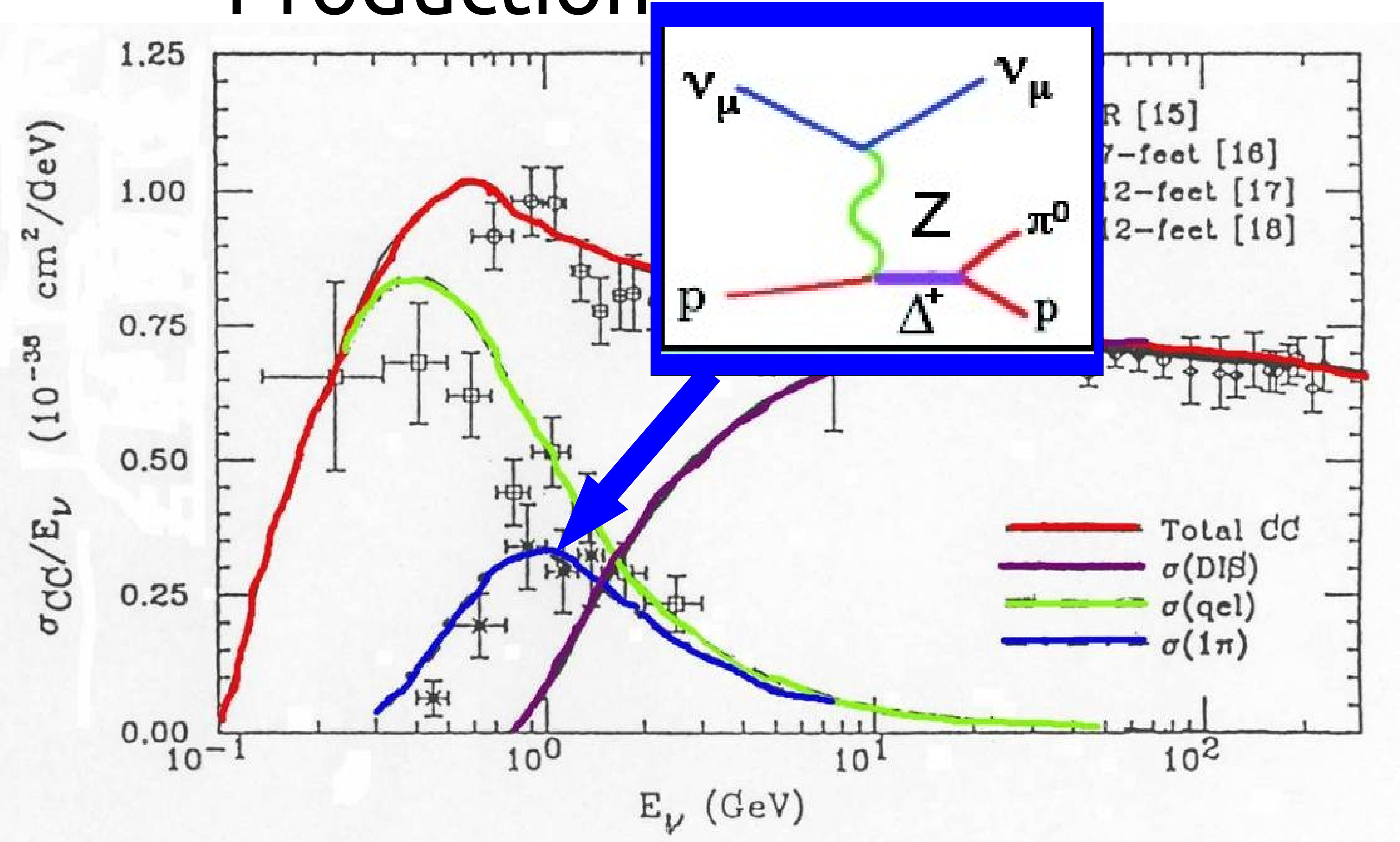
2. The outgoing nucleon can interact with the target nucleus.

This nuclear re-interaction affects the outgoing nucleon momentum and direction

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

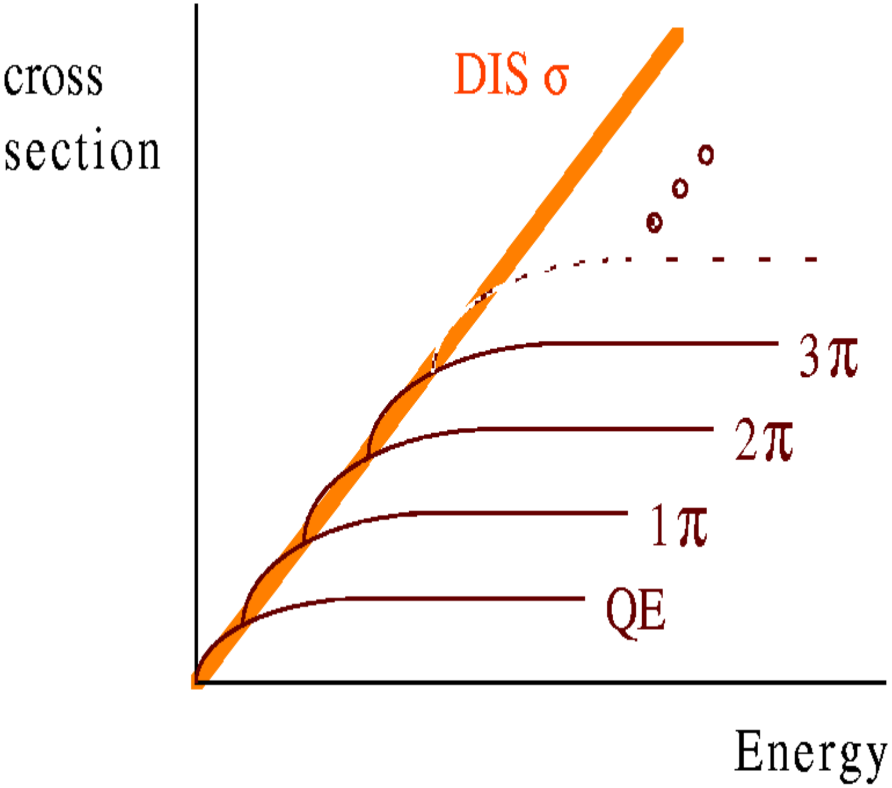
Resonance Production



Resonance production

Between elastic and inelastic scattering regions is a region associated with resonance production.

$$Invariant\ \ Mass^2 = W^2 = M_T^2 + 2 M_T \nu (1 - x)$$



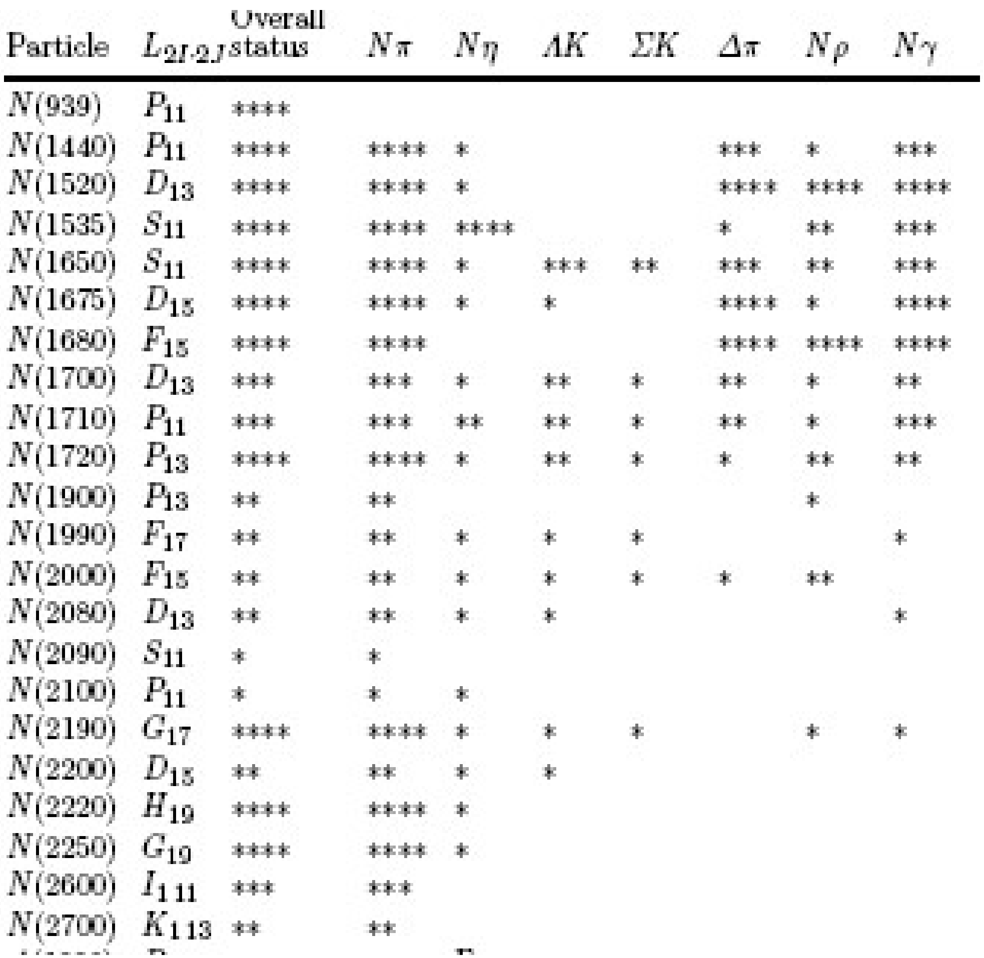
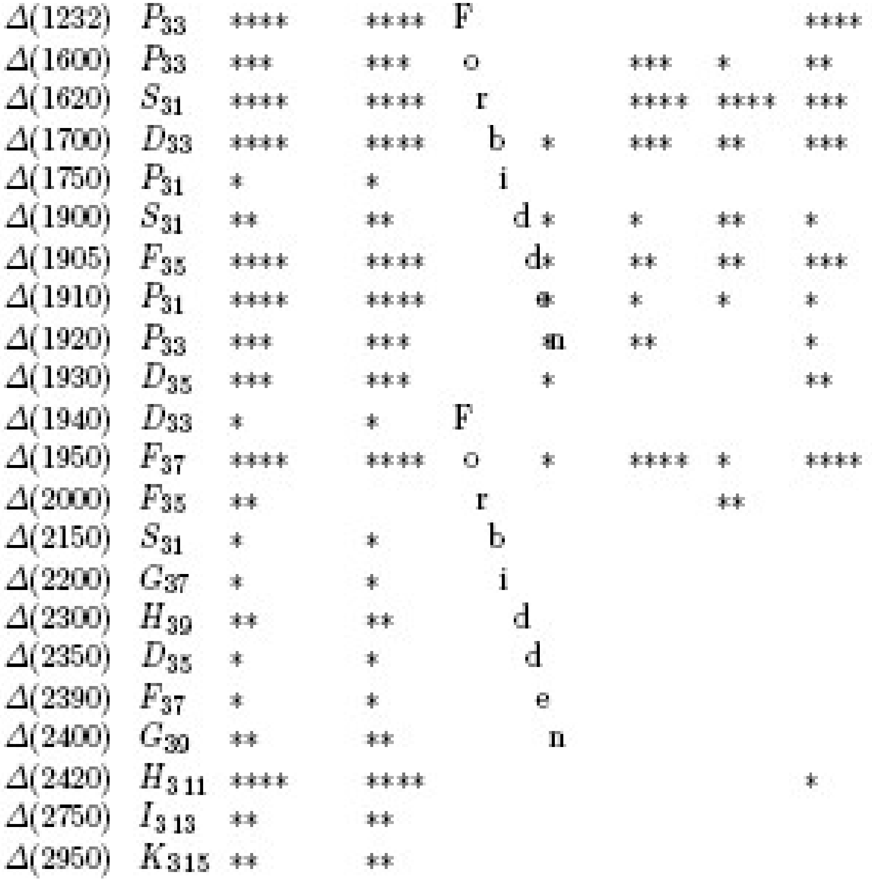
If x=1 then $W^2 = M_T^2 \Rightarrow$ (Quasi)-elastic scattering

$W^2 = (M_T + m_\pi)^2, (M_T + 2m_\pi)^2, \ldots$

Incredibly complicated region with different angular momentum, spin, parity resonances

dominated by the N* (S=0,I=1/2) and Δ (S=0,I=3/2)

Example

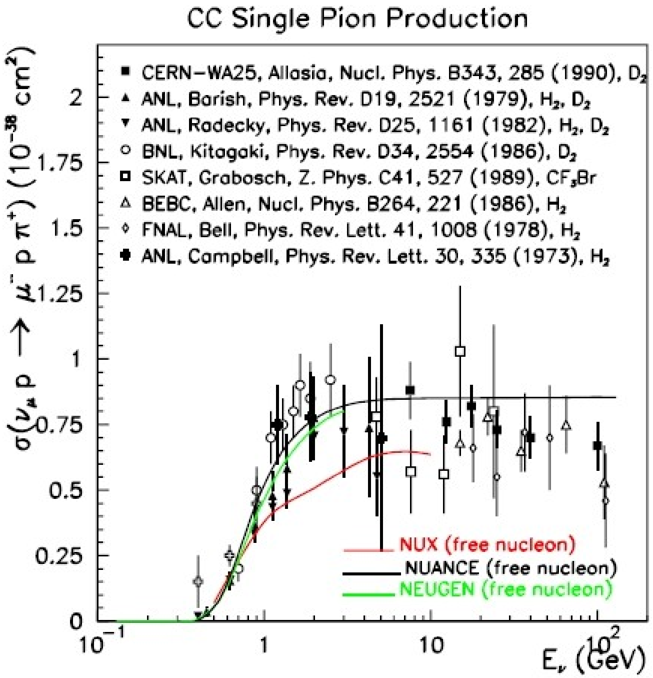



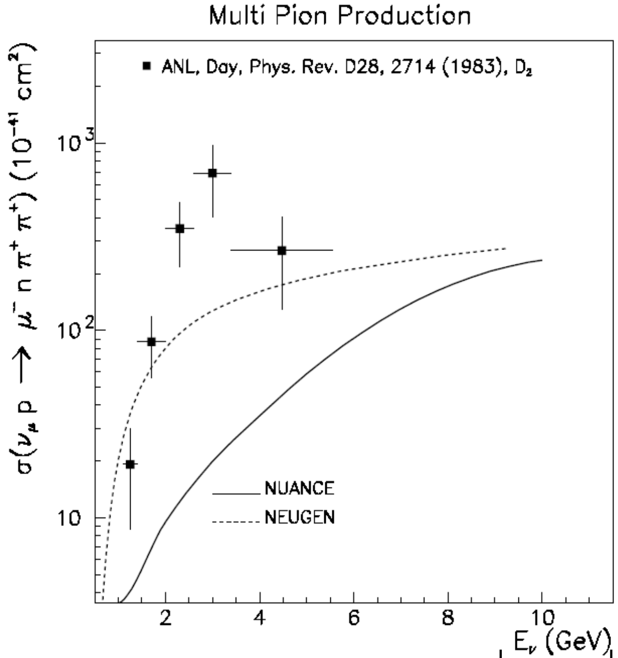
Particle	$L_{2I\cdot 2J}$	Overall status	$N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$N(939)$	P_{11}	****							
$N(1440)$	P_{11}	****	****	*			***	*	***
$N(1520)$	D_{13}	****	****	*			****	****	****
$N(1535)$	S_{11}	****	****	****			*	**	***
$N(1650)$	S_{11}	****	****	*	***	**	***	**	***
$N(1675)$	D_{15}	****	****	*	*		****	*	****
$N(1680)$	F_{15}	****	****				****	****	****
$N(1700)$	D_{13}	***	***	*	**	*	**	*	**
$N(1710)$	P_{11}	***	***	**	**	*	**	*	***
$N(1720)$	P_{13}	****	****	*	**	*	*	**	**
$N(1900)$	P_{13}	**	**					*	
$N(1990)$	F_{17}	**	**	*	*	*			*
$N(2000)$	F_{15}	**	**	*	*	*	*	**	
$N(2080)$	D_{13}	**	**	*	*				*
$N(2090)$	S_{11}	*	*						
$N(2100)$	P_{11}	*	*	*					
$N(2190)$	G_{17}	****	****	*	*	*		*	*
$N(2200)$	D_{15}	**	**	*	*				
$N(2220)$	H_{19}	****	****	*					
$N(2250)$	G_{19}	****	****	*					
$N(2600)$	$I_{1\,11}$	***	***						
$N(2700)$	$K_{1\,13}$	**	**						
$\Delta(1232)$	P_{33}	****	****	F					****
$\Delta(1600)$	P_{33}	***	***	o			***	*	**
$\Delta(1620)$	S_{31}	****	****	r			****	****	***
$\Delta(1700)$	D_{33}	****	****	b		*	***	**	***
$\Delta(1750)$	P_{31}	*	*	i					
$\Delta(1900)$	S_{31}	**	**	d		*	*	**	*
$\Delta(1905)$	F_{35}	****	****	d		*	**	**	***
$\Delta(1910)$	P_{31}	****	****	e		*	*	*	*
$\Delta(1920)$	P_{33}	***	***	n		*	**		*
$\Delta(1930)$	D_{35}	***	***			*			**
$\Delta(1940)$	D_{33}	*	*	F					
$\Delta(1950)$	F_{37}	****	****	o		*	****	*	****
$\Delta(2000)$	F_{35}	**		r				**	
$\Delta(2150)$	S_{31}	*	*	b					
$\Delta(2200)$	G_{37}	*	*	i					
$\Delta(2300)$	H_{39}	**	**	d					
$\Delta(2350)$	D_{35}	*	*	d					
$\Delta(2390)$	F_{37}	*	*	e					
$\Delta(2400)$	G_{39}	**	**	n					
$\Delta(2420)$	$H_{3\,11}$	****	****						*
$\Delta(2750)$	$I_{3\,13}$	**	**						
$\Delta(2950)$	$K_{3\,15}$	**	**						

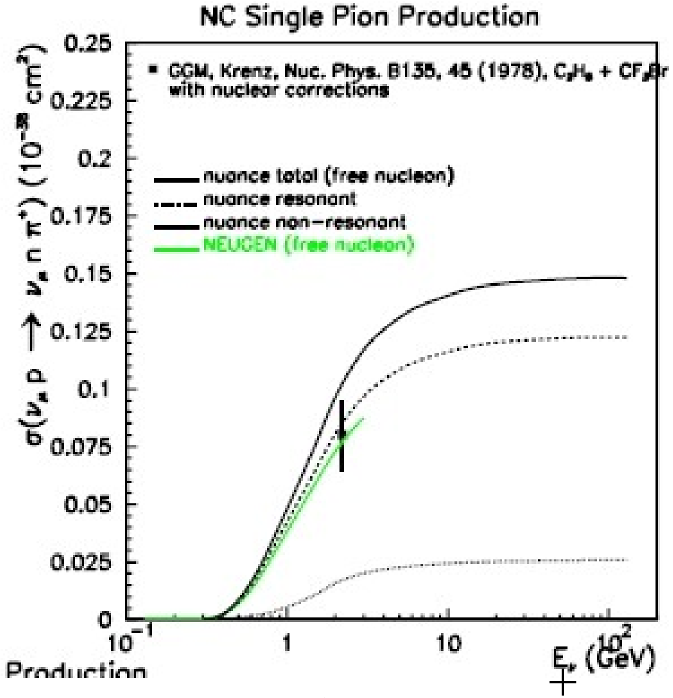
Different states can interfere in production amplitudes
Some states do not take part due to helicity structure

Resonance Region Data

The data is impressively imprecise





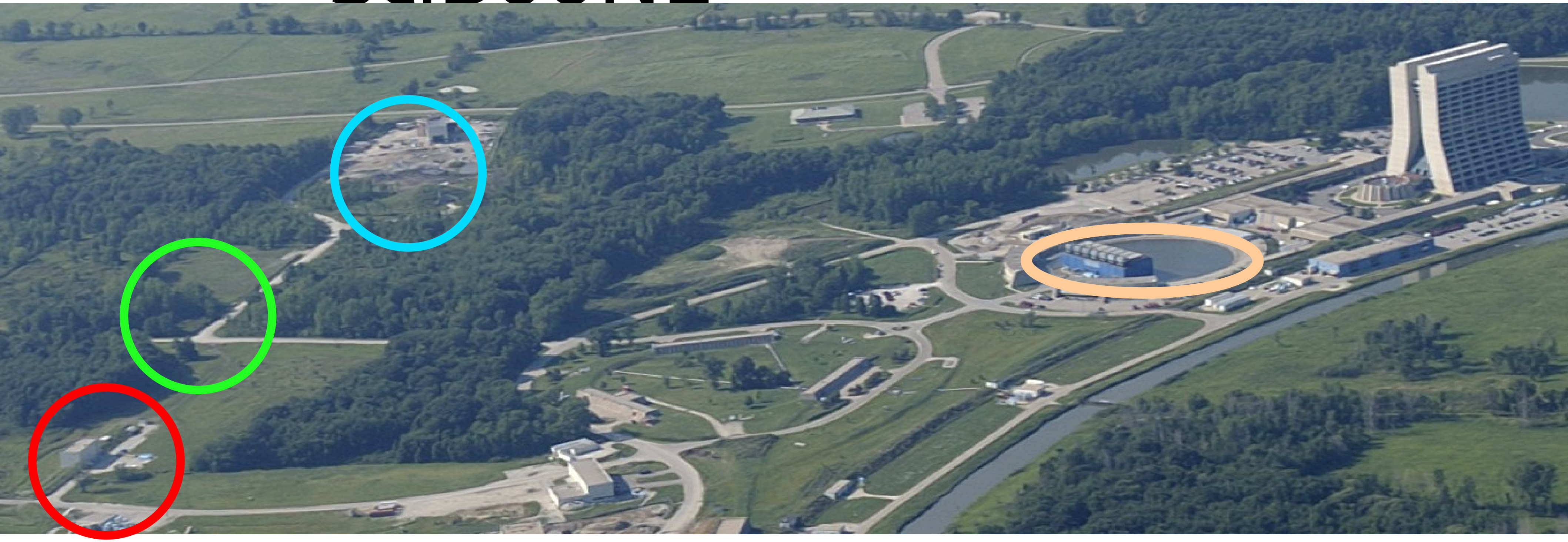


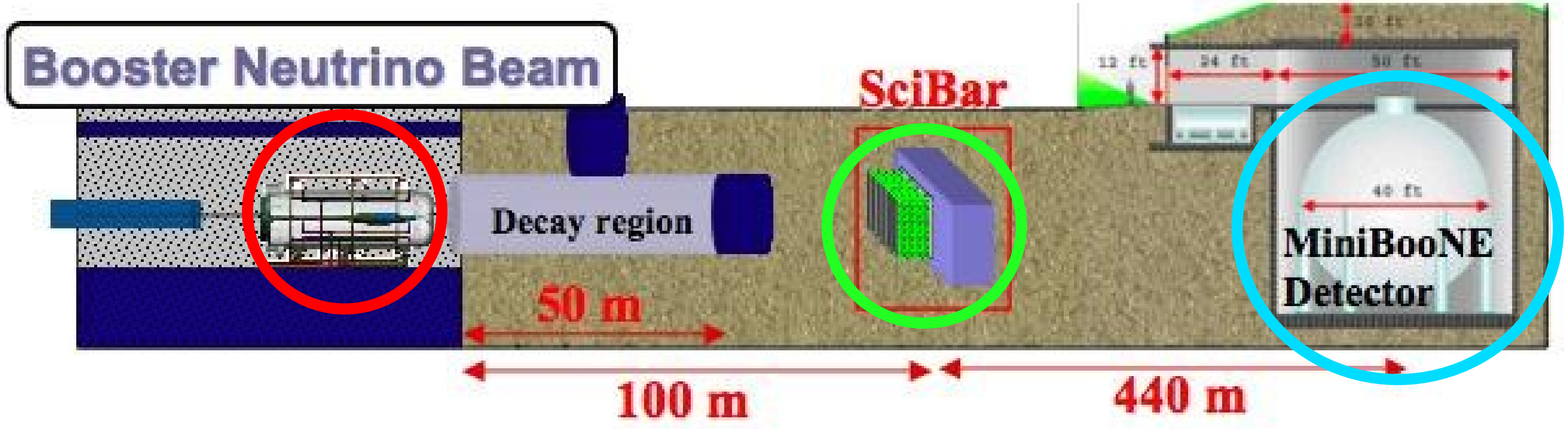
$\nu_\mu p \to \mu^- p \pi^+$ $\nu_\mu p \to \mu^- n \pi^+ \pi^+$ $\nu_\mu p \to \nu_\mu n \pi^+$

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

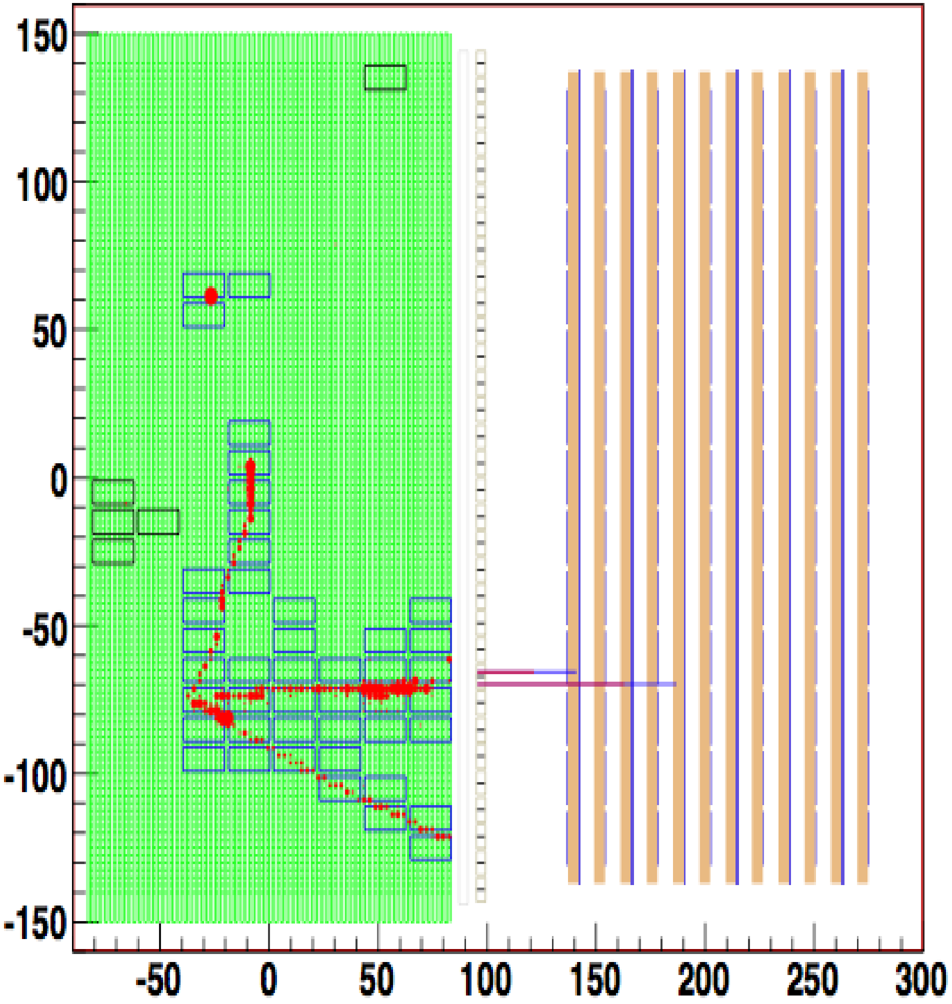
$\pi^+ n \to \pi^0 p$

SciBooNE




Booster Neutrino Beam
SciBar
12 ft
24 ft
50 ft
40 ft
Decay region
MiniBooNE Detector
50 m
100 m
440 m

SciBoone

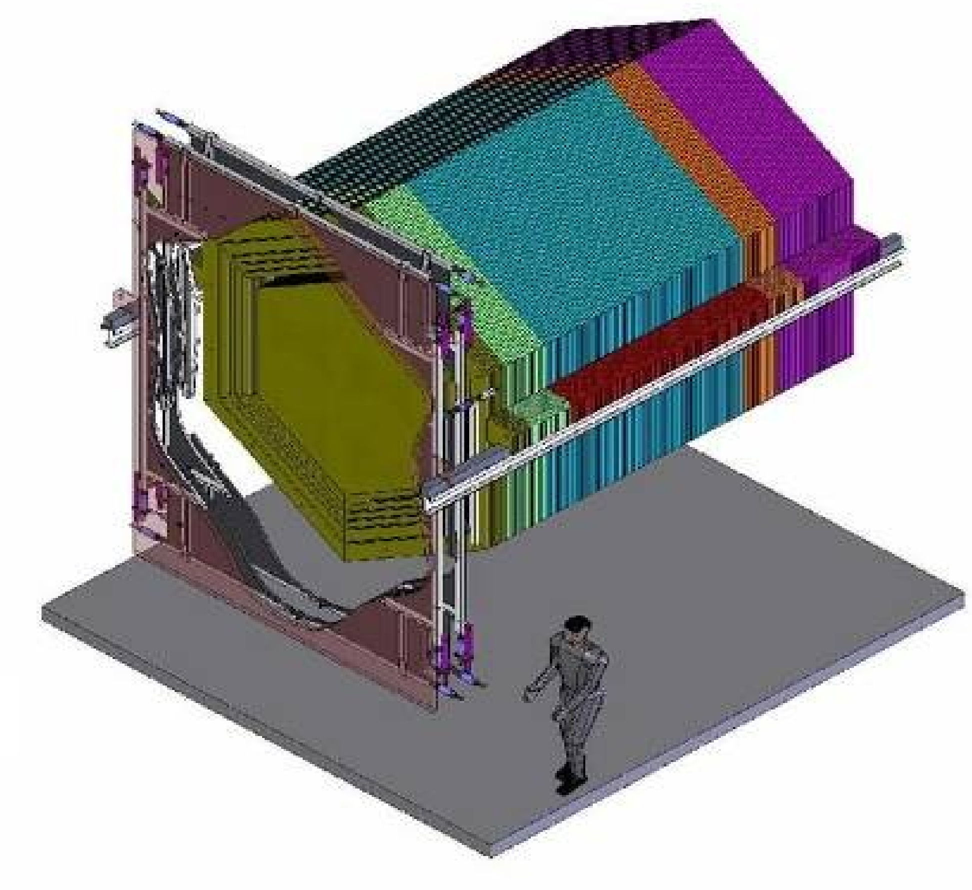


- SciBooNE already running!
- 2 years from formation of collaboration to first data!

CHANNEL	ν	Anti- ν
CCQE	39k	7.5k
$CC1\pi^+$	24k	2k
$NC1\pi^0$	9k	1.3k
NC Coherent	0.8k	0.3k

MINERνA

- Active core is segmented solid scintillator
  - Tracking (including low momentum recoil protons)
  - Particle identification by energy deposition (dE/dx)
  - 3 ns (RMS) per hit timing (track direction, identify stopped $K^{\pm}$)
- Core surrounded by electromagnetic and hadronic calorimeters
  - Photon (π^0) & hadron energy measurement
- Upstream region has simultaneous C, Fe, Pb, He targets to study nuclear effects
- MINOS Near Detector as muon catcher



MINERνA

WARWICK
THE UNIVERSITY OF WARWICK

Fiducial Mass : 3 ton CH, 0.6 ton C, 1 ton Fe, 1 ton Pb

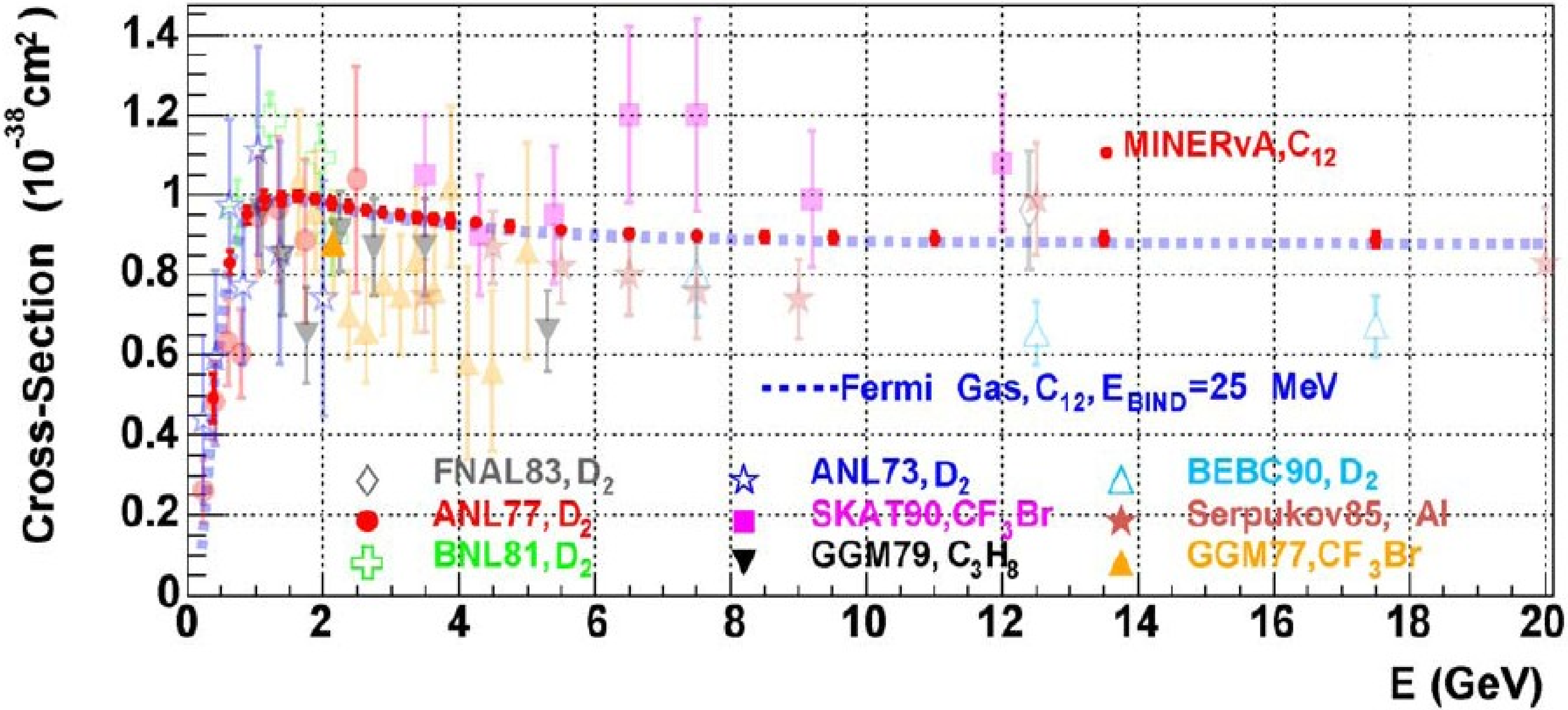
Total Event rate

Target	CC ν Rate
CH	8.6 M
C	1.4 M
Fe	2.9 M
Ph	2.9 M

Physics Event rate in CH

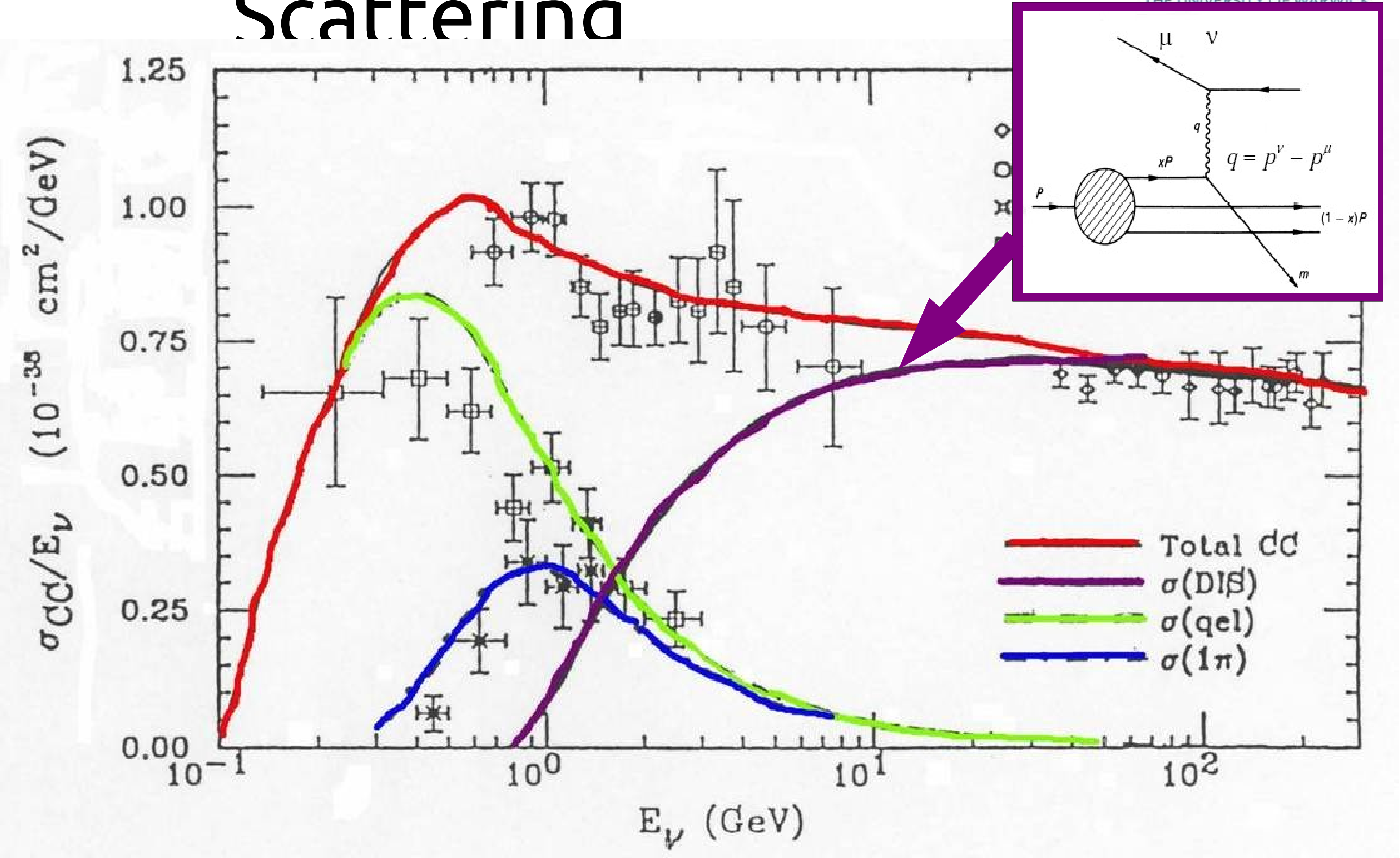
Process	Rate
QE	0.8 M
1 pion	1.6 M
Transition	2.0 M
DIS	4 M

CCQE Cross section



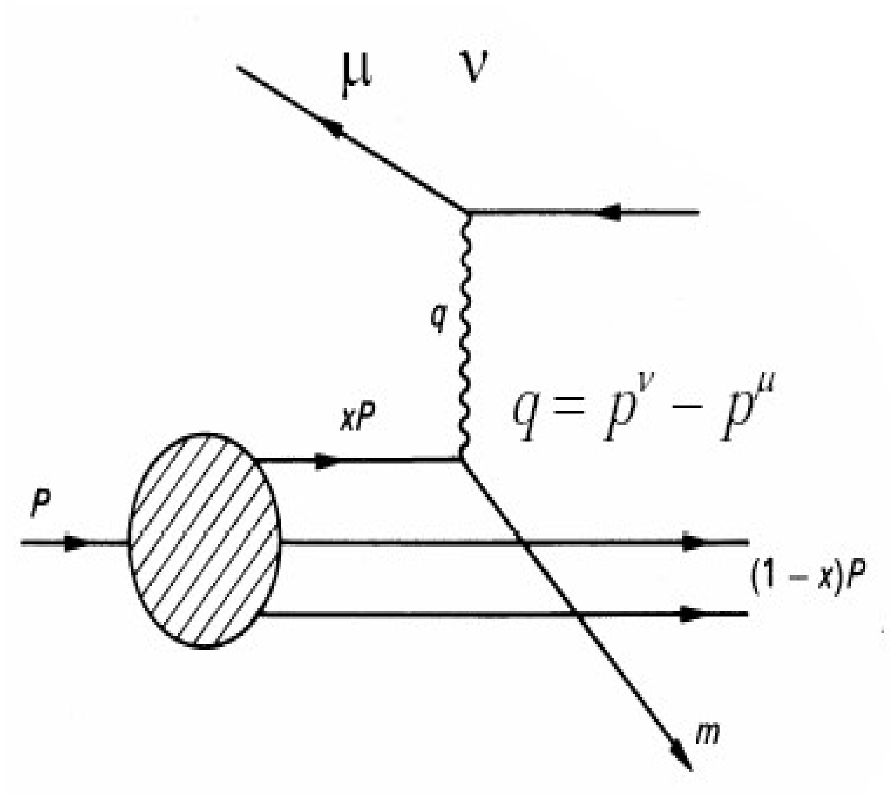
High efficiency and purity (~ 77% and ~ 74% resp.
Nuclear Effects can be studied in nuclear targets
Deviation from dipole form factors can be studied

Deep Inelastic Scattering



Deep Inelastic Scattering

In DIS, the neutrino is pictured as scattering off a free parton within the nucleon



In “infinite momentum frame” all partons are moving collinear to direction of motion of nucleon and are asymptotically free

x can be thought of as the fraction of nucleon momentum carried by the struck quark

$$mass\,of\;FS\,quark = m_q^2 = (xP + q)^2$$

If $Q^2 >> m_q^2, M_T^2 \Rightarrow x = Q^2/2P.q$

$0 < x < 1$

DIS Cross section

Situation : neutrino scattering off massive point-like object

This is *almost* exactly the same as ν-e scattering

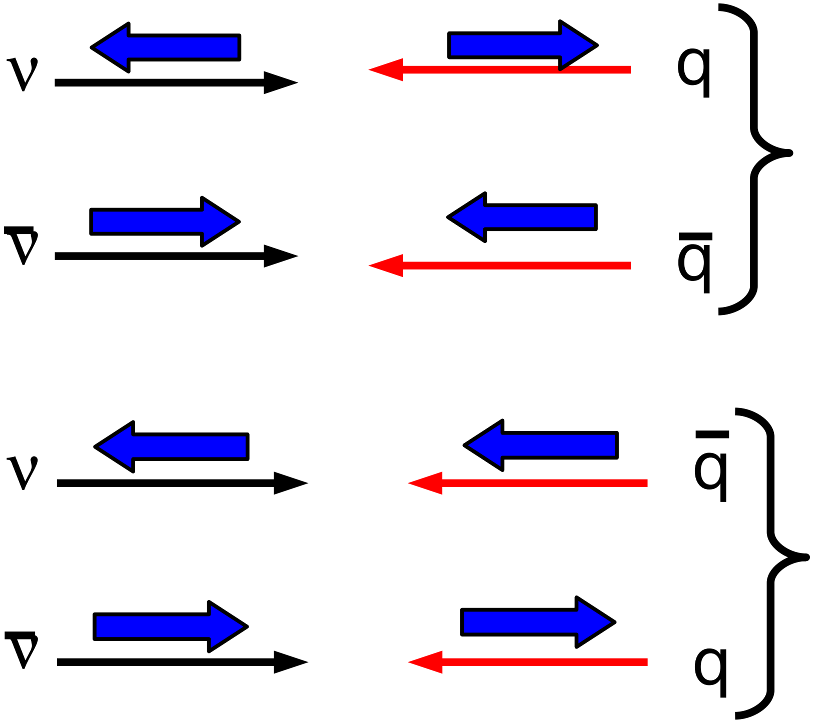
Pointlike scattering

$$\frac{d^2\sigma^{\nu q}}{dx\,dy}=\frac{G_F^2 s}{\pi}q(x)$$

$$\frac{d^2\sigma^{\nu \bar{q}}}{dx\,dy}=\frac{G_F^2 s}{\pi}\bar{q}(x)(1-y)^2$$

Parton distribution function

Chiral structure



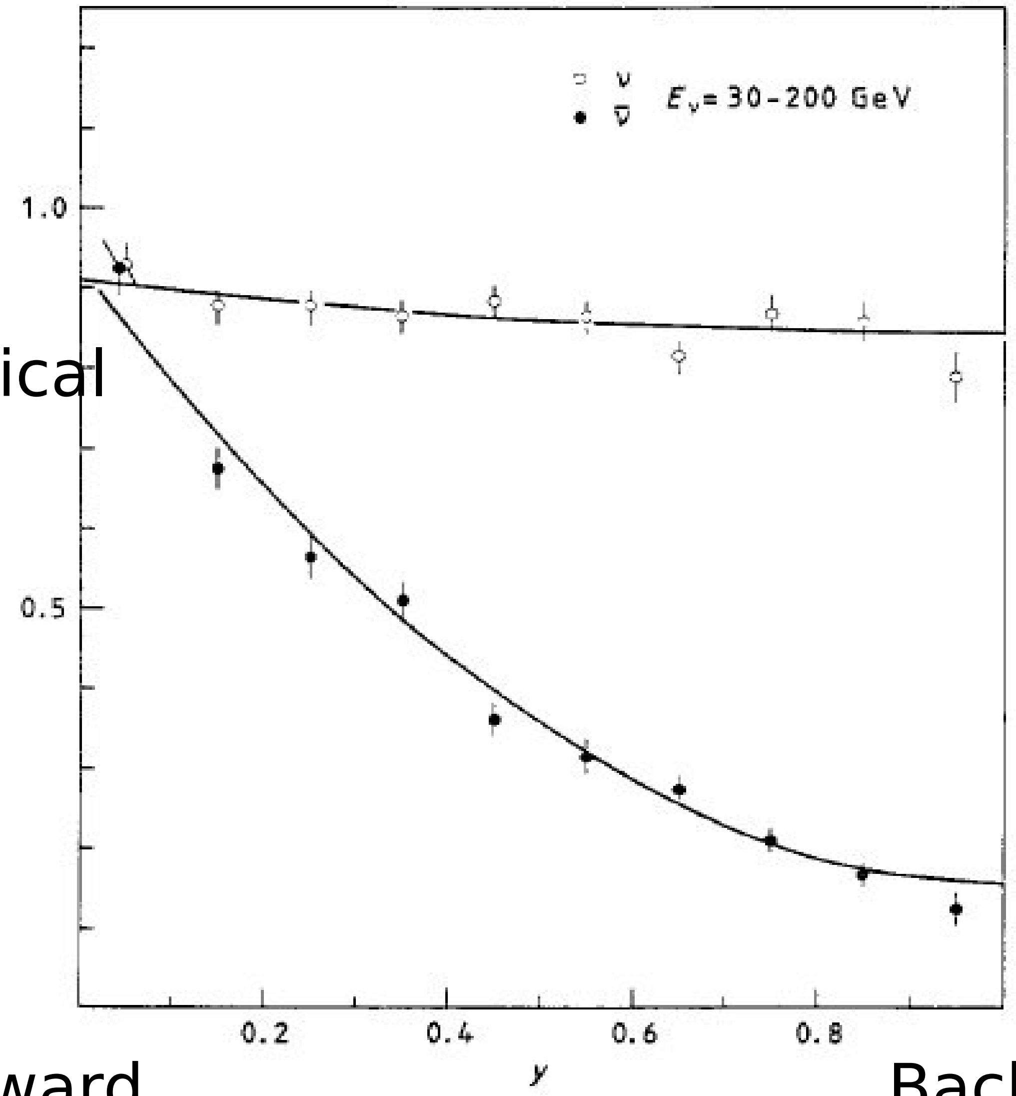
Δs=0
Flat in y
$\nu q, \bar{\nu}\bar{q}$

Δs=1
$(1\text{-}y)^2$
$\bar{\nu}q, \nu\bar{q}$

Y-distribution in DIS

(From CDHS)

Y=0
ν and $\bar{\nu}$
are identical



At y=1, neutrinos
see only quarks

Antineutrinos see
only antiquarks

Forward
Scattering

Backward
Scattering

Parton Distributions

The probability of finding a quark of flavour 'q' in the nucleon with fractional momentum x is q(x).
The number of quarks of flavour q with fractional momenta between x and x+dx is q(x)dx

Factorisation Theorem of QCD

$$A(l+h \rightarrow l'+H) = \sum_q A(l+q(x) \rightarrow l'+X)\, q_h(x)$$

Int. of lepton with hadron

Int. of lepton with a quark

P(q ∈ h)

- Parton distributions ($q_h(x)$=pdf) are universal
- Are not yet calculable (so we need to measure them)

Scattering from Nucleons

Proton = uud + $(u\bar{u})$ + $(d\bar{d})$ + $(s\bar{s})$ + $(c\bar{c})$

$$\frac{d^2\sigma(CC\nu p)}{dx\,dy}=\frac{G_F^2 s}{\pi}[(xd(x)+xs(x))+(\bar{u}(x)+\bar{c}(x))(1-y)^2]$$

$$\frac{d^2\sigma(CC\bar{\nu} p)}{dx\,dy}=\frac{G_F^2 s}{\pi}[(xu(x)+xc(s))(1-y)^2+(\bar{d}(x)+\bar{s}(x))]$$

To get the cross section for scattering from a neutron

Neutron = ddu + $(\bar{u}u)$ + $(\bar{d}d)$ + $(\bar{s}s)$ + $(\bar{c}c)$

Isospin Symmetry

$u_n(x)=d_p(x)=d(x)$

$d_n(x)=u_p(x)=u(x)$

$s_n(x)=s_p(x)=s(x)$

$c_n(x)=c_p(x)=c(x)$

$$\frac{d^2\sigma(CC\nu n)}{dx\,dy}=\frac{G_F^2 s}{\pi}[(xu(x)+xs(x))+(\bar{d}(x)+\bar{c}(x))(1-y)^2]$$

$$\frac{d^2\sigma(CC\bar{\nu} n)}{dx\,dy}=\frac{G_F^2 s}{\pi}[(xd(x)+xc(s))(1-y)^2+(\bar{u}(x)+\bar{s}(x))]$$

Or…we can use structure functions

A model independent picture can be formed using nucleon structure functions

$$\frac{d^2\sigma^{\nu,\bar{\nu}}}{dx\,dy}=\frac{G_F^2 s}{\pi}[y^2 2x F_1(x,Q^2)+2(1-y-\frac{Mxy}{2E})F_2(x,Q^2)\pm 2\mathrm{y}(1-\frac{y}{2})xF_3(x,Q^2)]$$

F_i are related to the helicity-structure of the q-W interaction

For massless spin-1/2 partons we can make a simplification

Callen-Gross Relation : $2xF_1 = F_2$

$$\frac{d^2\sigma^{\nu,\bar{\nu}}}{dx\,dy}=\frac{G_F^2 s}{\pi}[((1-y)^2+(1-\frac{Mxy}{2E}))F_2(x,Q^2)\pm 2\mathrm{y}(1-\frac{y}{2})xF_3(x,Q^2)]$$

Structure functions must (again) be measured

Relationship to q(x)

One can relate F_i to the pdf's by matching the y-dependence

Assuming the Callen-Gross relationship, massless partons and targets.......

$$F_2^{\nu p,CC} = x\left[d_p(x) + \overline{u}_p(x) + s_p(x) + \overline{c}_p(x)\right]$$

$$xF_3^{\nu p,CC} = x\left[d_p(x) - \overline{u}_p(x) + s_p(x) - \overline{c}_p(x)\right]$$

For an *isoscalar* target (equal numbers of protons and neutrons)

$$q = u + d + s + c\,;\; \overline{q} = \overline{u} + \overline{d} + \overline{s} + \overline{c}$$

$$F_2^{\nu N,CC} = x\left[q(x) + \overline{q}(x)\right]$$

$$xF_3^{\nu N,CC} = x\left[q(x) - \overline{q}(x)\right]$$

Cross section

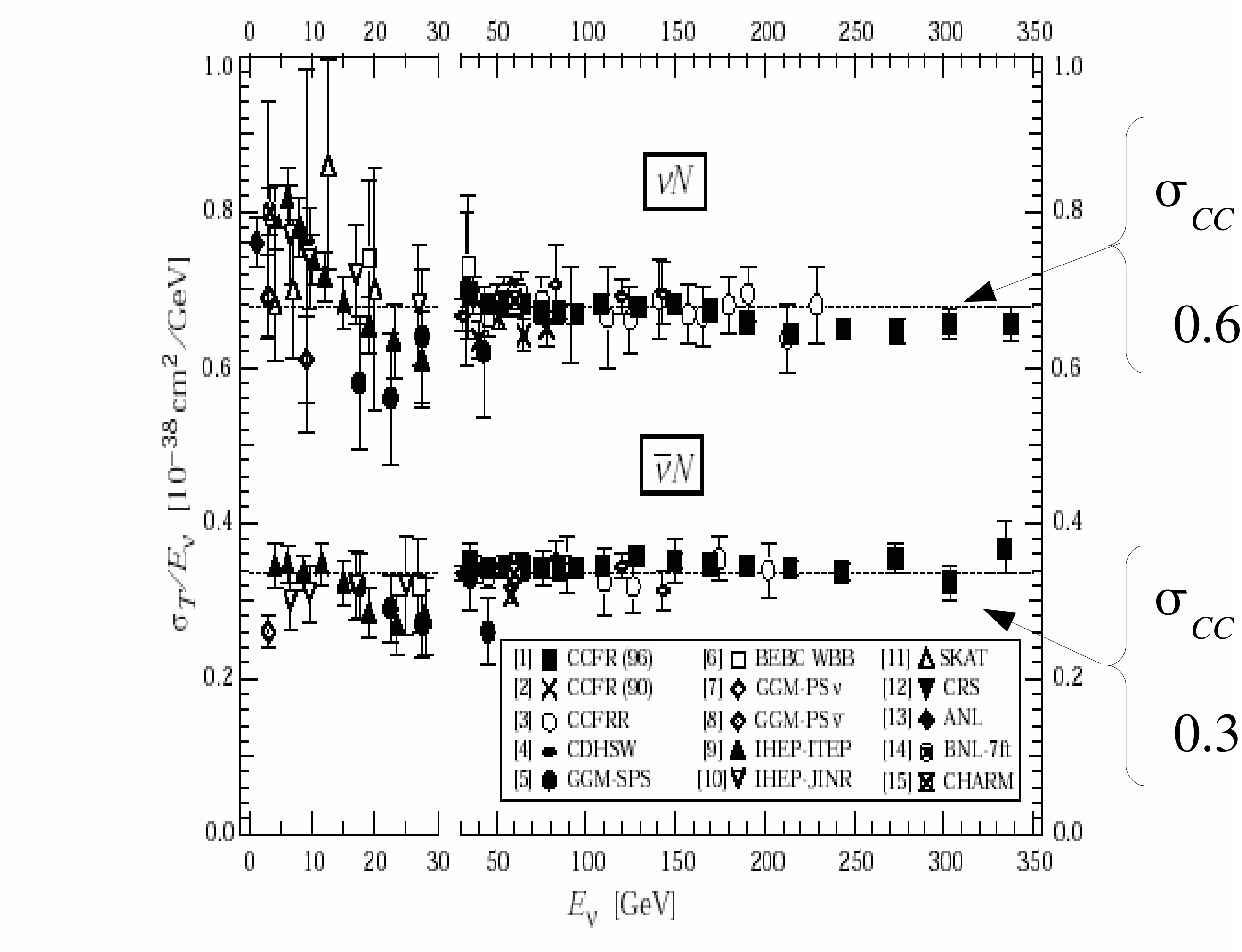


Figure 39.10: σ_T/E_ν, for the muon neutrino and anti-neutrino charged-current total cross section as a function of neutrino energy. The error bars include both statistical and systematic errors. The straight lines are the averaged values over all energies as measured by the experiments in Refs. [1–4]: = 0.677 ± 0.014 (0.334 ± 0.008) $\times 10^{-38}$ cm^2/GeV. Note the change in the energy scale at 30 GeV. (Courtesy W. Seligman and M.H. Shaevitz, Columbia University, 2001.)

$$\sigma_{CC}(\nu N) = \frac{G_F^2 s}{\pi}\left[Q + \frac{1}{3}\overline{Q}\right]$$

$$0.67 \times 10^{-38} E_\nu \, cm^2/GeV$$

$$\sigma_{CC}(\bar{\nu} N) = \frac{G_F^2 s}{\pi}\left[\frac{1}{3}Q + \overline{Q}\right]$$

$$0.34 \times 10^{-38} E_\nu \, cm^2/GeV$$

Proof that sea quarks exist!

Neutral Currents

As with ν-e scattering, the NC interaction contains both V-A and V+A contributions.
All quark flavours participate in the interaction
u and d quarks contribute different coupling constants for Left and Right-handed states.

So instead of this

$$F_2^{\nu p, CC} = x[d_p(x) + \overline{u}_p(x) + s_p(x) + \overline{c}_p(x)]$$
$$xF_3^{\nu p, CC} = x[d_p(x) - \overline{u}_p(x) + s_p(x) - \overline{c}_p(x)]$$

Neutral Currents

As with ν-e scattering, the NC interaction contains both V-A and V+A contributions.
All quark flavours participate in the interaction
u and d quarks contribute different coupling constants for Left and Right-handed states.

You get this....

$$F_2^{\nu p,NC} = x[(g_{L,u}^2 + g_{R,u}^2)(u(x)+\bar{u}(x)+c(x)+\bar{c}(x))]$$
$$+x[(g_{L,d}^2 + g_{R,d}^2)(d(x)+\bar{d}(x)+s(x)+\bar{s}(x))]$$

$$xF_3^{\nu p,NC} = x[(g_{L,u}^2 - g_{R,u}^2)(u(x)-\bar{u}(x)+c(x)-\bar{c}(x))]$$
$$+x[(g_{L,d}^2 - g_{R,d}^2)(d(x)-\bar{d}(x)+s(x)-\bar{s}(x))]$$

$$g_{L,u} = \frac{1}{2}\left(1-\frac{4}{3}\sin^2\theta_W\right);\ g_{R,u} = \frac{-2}{3}\sin^2\theta_W$$

$$g_{L,d} = \frac{1}{2}\left(-1+\frac{2}{3}\sin^2\theta_W\right);\ g_{R,d} = \frac{1}{3}\sin^2\theta_W$$

So....what?

Define :
$$R^{\nu}=\frac{\sigma_{NC}(\nu N)}{\sigma_{CC}(\nu N)};R^{\bar{\nu}}=\frac{\sigma_{NC}(\bar{\nu} N)}{\sigma_{CC}(\bar{\nu} N)};r=\frac{\sigma_{CC}(\nu N)}{\sigma_{CC}(\overline{\nu N})}$$

Then
$$R^{\nu}=\frac{1}{2}-\sin^2\theta_W+(1+r)\frac{5}{9}\sin^4\theta_W$$
$$R^{\bar{\nu}}=\frac{1}{2}-\sin^2\theta_W+(1+\frac{1}{r})\frac{5}{9}\sin^4\theta_W$$

Llewellyn-Smith relationships

$$\sin^2\theta_W=0.223\pm0.003\pm0.005$$

0.2227 ± 0.00037 (world average)

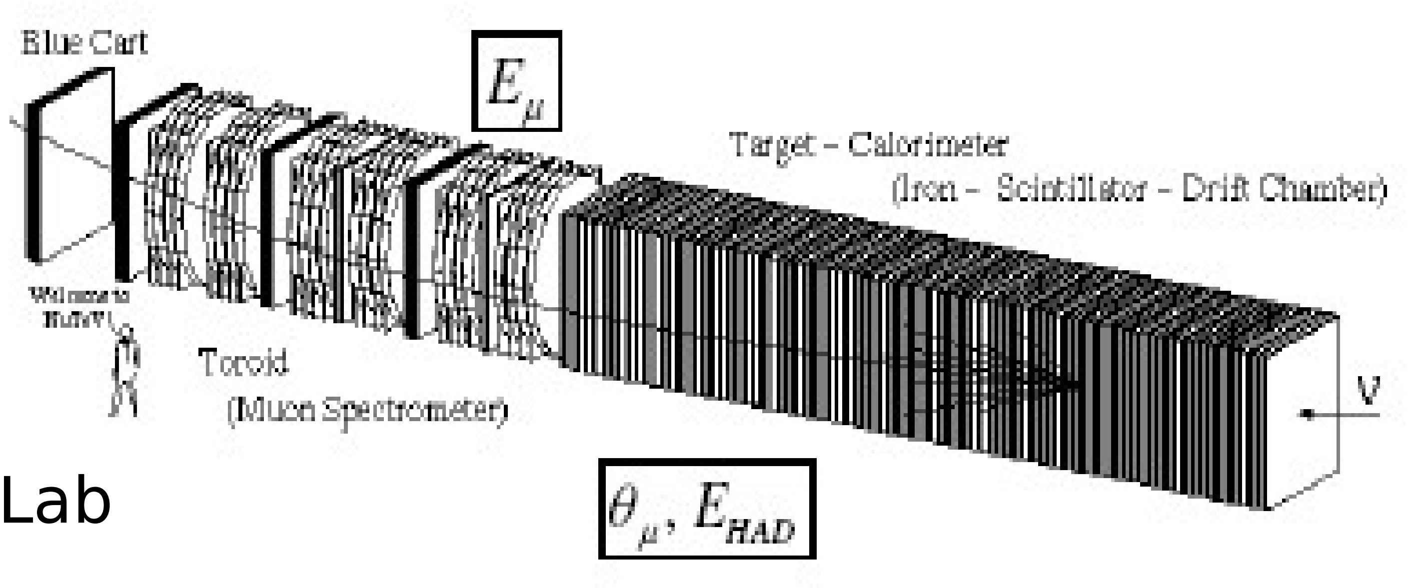
From CHARM,CDHS,CCFR

Status of $\sin^2\theta_W$

NuTeV was the last experiment to make a precision measurement of $\sin\theta_W$ in neutrino interactions

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
- Used unique sign selected beam – NuTeV had pure neutrino and antineutrino data samples

NuTeV Fit

$$\sin^2\theta_W^{(on-shell)} = 0.2277 \pm \pm 0.0013(stat.) \pm 0.0009(syst.)$$

$$= 0.2277 \pm 0.0016$$

(Previous neutrino measurements gave 0.2277 ± 0.0036)

- Standard model fit (LEPEWWG): 0.2227 ± 0.00037

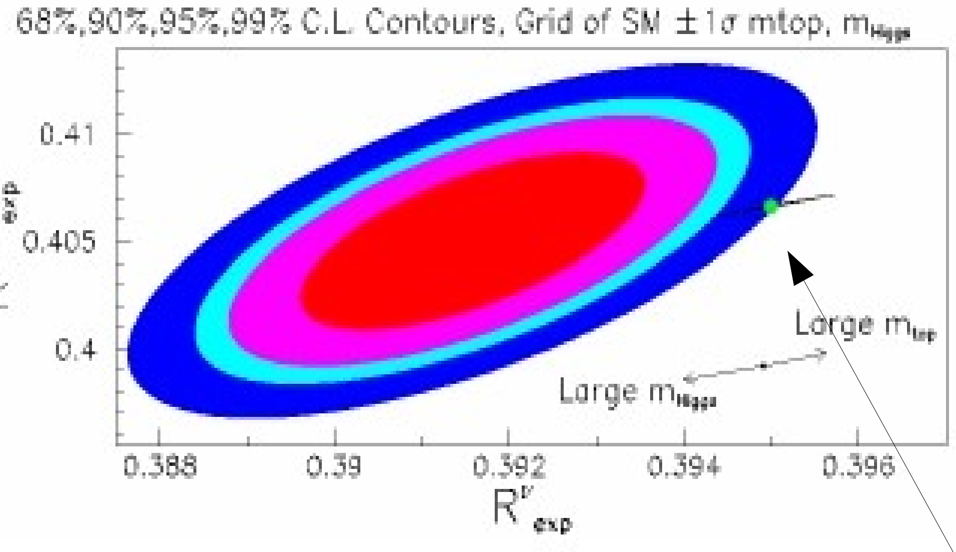
A 3σ discrepancy ....

$R^{\nu}_{\mathrm{exp}} = 0.3916 \pm 0.0013$

$(SM : 0.3950) \quad \Leftarrow 3\sigma$ *difference*

$R^{\bar{\nu}}_{\mathrm{exp}} = 0.4050 \pm 0.0027$

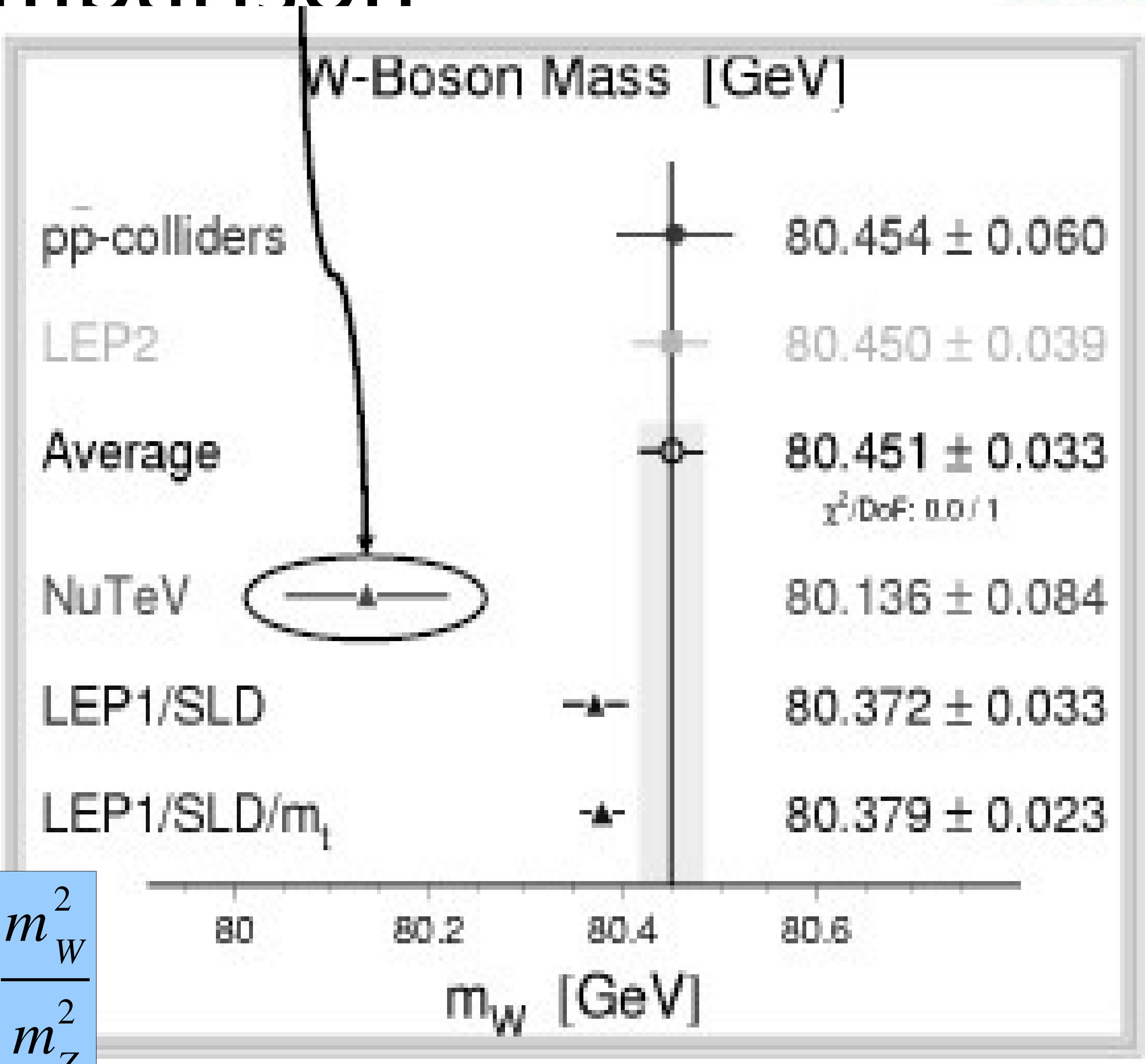
$(SM : 0.4066) \quad \Leftarrow$ *Good agreement*



$$R^{\nu} = \frac{\sigma_{NC}(\nu N)}{\sigma_{CC}(\nu N)}; R^{\bar{\nu}} = \frac{\sigma_{NC}(\bar{\nu} N)}{\sigma_{CC}(\bar{\nu} N)}$$

Standard Model measurement

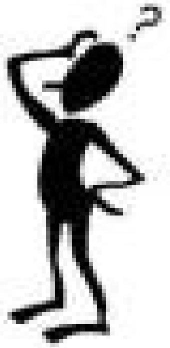
Comparison



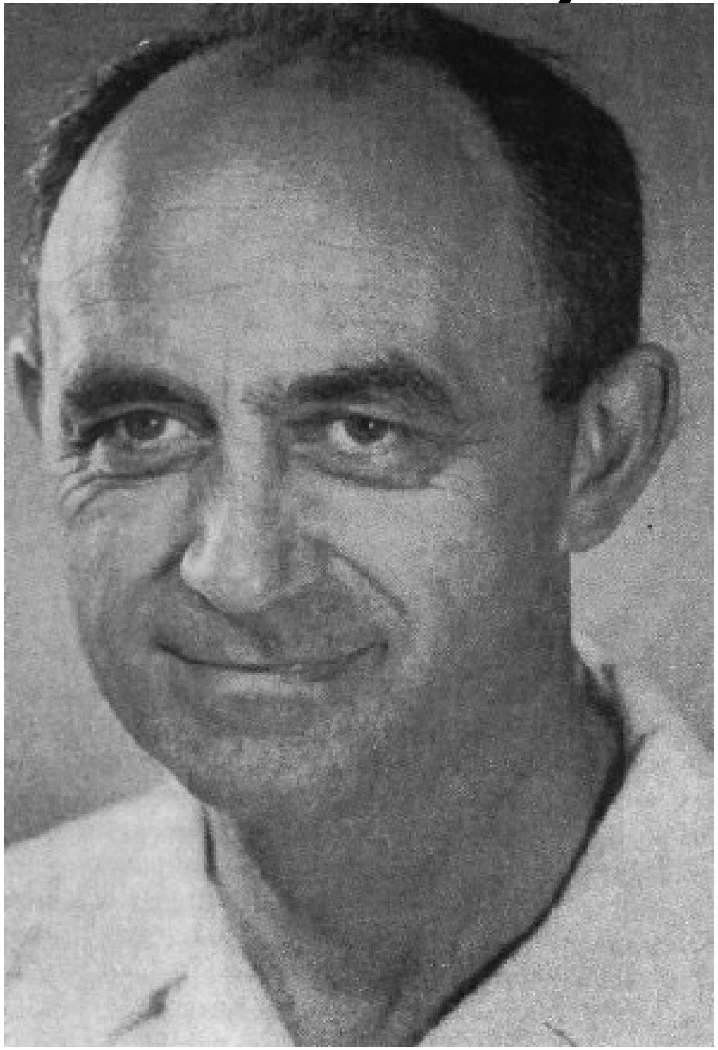
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

Possible interpretations

- *New Beyond-Standard-Model physics?*
  - Difficult to find something which does this just for ν
- *Purely experimental*
  - Multiple checks. Not obvious if it is.
- *Mundane explanations*
  - Charm mass effects
  - Radiative effects
  - Isospin symmetry violation : $u_p(x) \neq d_n(x)$
  - Strange/anti-Strange sea asymmetry : $s(x) \neq s(x)$ (intrinsic strangeness?)
  - Different nuclear effects for NC over CC (Z over W)



Fermi Theory (1926-34)



Initial paper rejected by Nature because:

“it contains speculations to remote from reality to be of interest to the reader”

Neutral Currents

The electroweak theory of Glashow, Weinberg and Salam predicted two types of weak interactions rather than just one, as predicted by V-A Fermi theory

Charged current : $\nu_l + X \rightarrow l + X'$ (l$^-$, ν)(l$^+$,$\bar{\nu}$)

Neutral current : $\nu_l + X \rightarrow \nu_l + X'$ Flavour blind

Interpreted as the exchange of two IVBs : $W^\pm$, Z^0

Discovery by Gargamelle bubble chamber in 1970 very controversial at the time. It was to take another year before the claims were verified

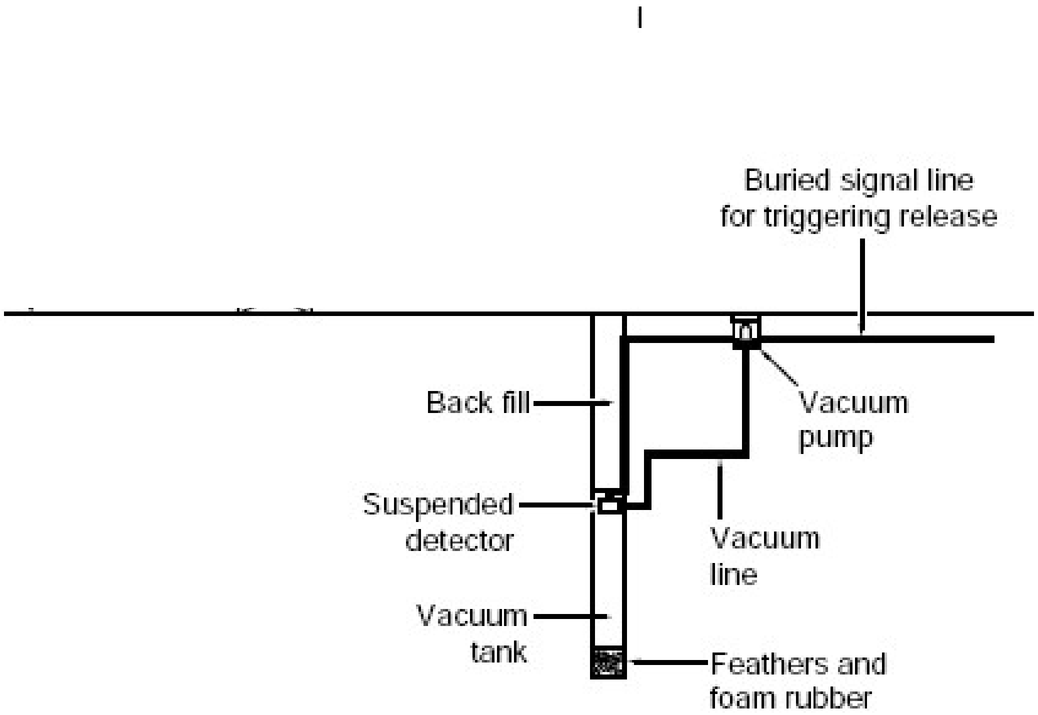
$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e-$$

Oh the pain

"I have done something very bad today by proposing a particle that cannot be detected. It is something that no theorist should ever do."

Pauli, 1930

Project Poltergeist - 1951



Build a deep hole and evacuate it

Suspend a detector above the pit

Spin & helicity

Spin: Intrinsic angular momentum

$$\Sigma_i = \sigma^{jk} = \frac{i}{2}\varepsilon_{ijk}\gamma^j\gamma^k = \begin{pmatrix}\sigma_i & 0 \\ 0 & \sigma_i\end{pmatrix}$$

Helicity: projects spin along the momentum

$$\Lambda = \vec{\Sigma}\cdot\frac{\vec{p}}{|\vec{p}|}$$

Projection operators project the components of positive and negative helicity out of an arbitrary spinor.

$$P_\pm\psi = \frac{1\pm\Lambda}{2}\psi$$

Reminder

$$(i\gamma^{\mu}\frac{\partial}{\partial x^{\mu}} - m)\psi(x) = 0$$

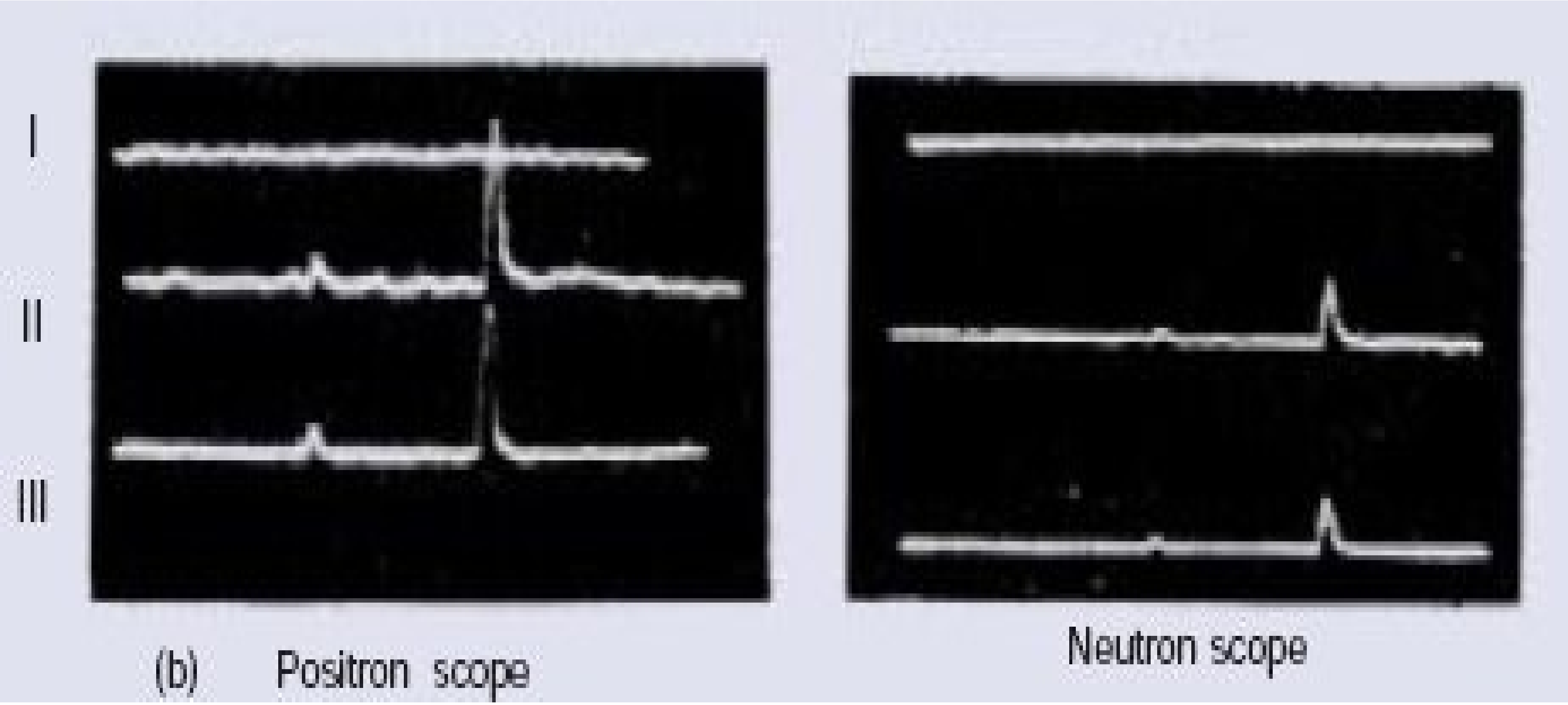
Dirac equation

$$\psi(x) = \begin{bmatrix}\psi_1\\ \psi_2\\ \psi_3\\ \psi_4\end{bmatrix} \quad \gamma^0 = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}, \quad \gamma^i = \begin{pmatrix} 0 & \sigma_i \\ \sigma_i & 0 \end{pmatrix}$$

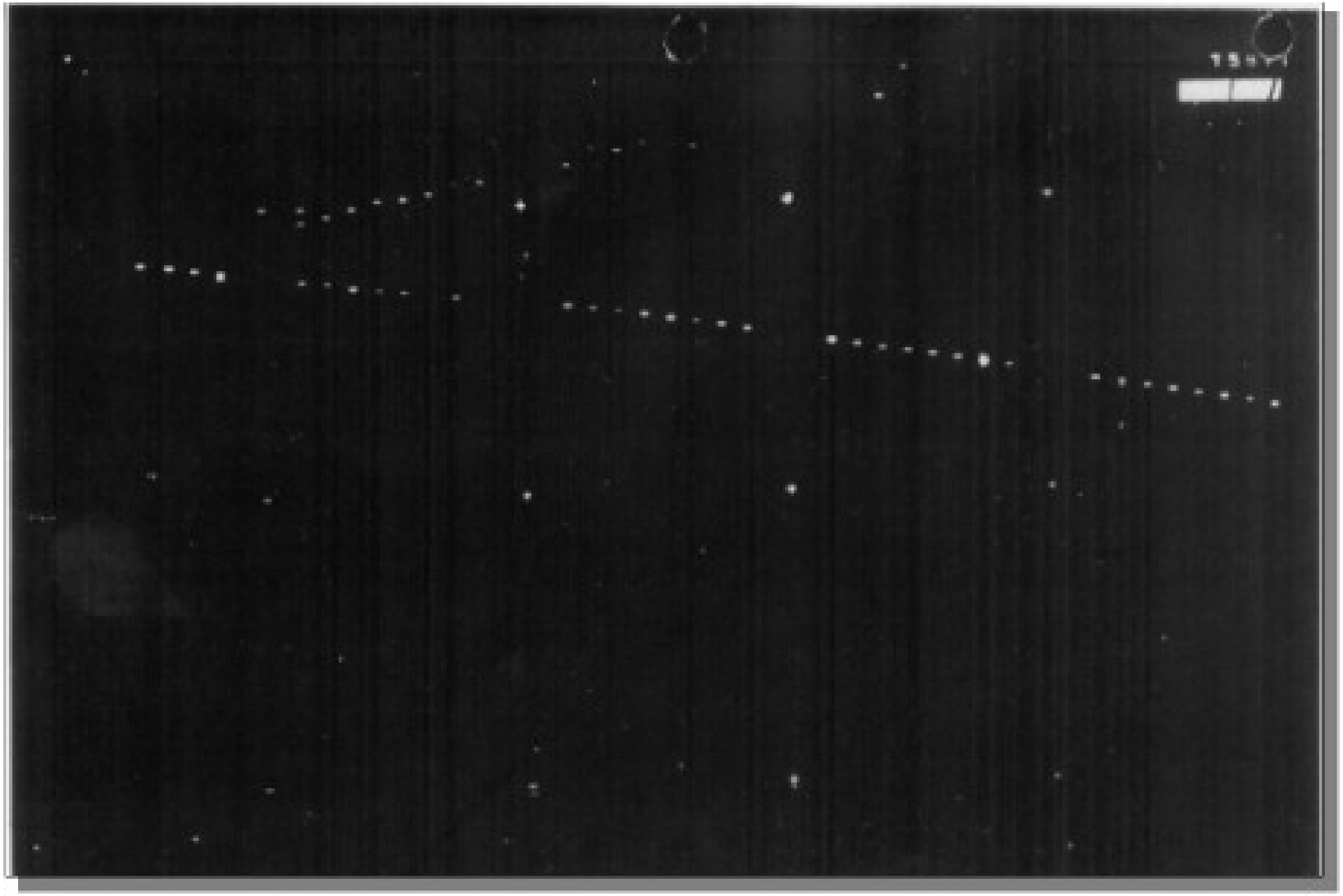
$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\gamma_5 = i\gamma_0\gamma_1\gamma_2\gamma_3 \;\; ; \;\; \gamma_5^{adj} = \gamma^5 \;\; : \;\; (\gamma_5)^2 = 1 \;\; : \;\; \gamma_5\gamma_\mu = -\gamma_\mu\gamma_5$$

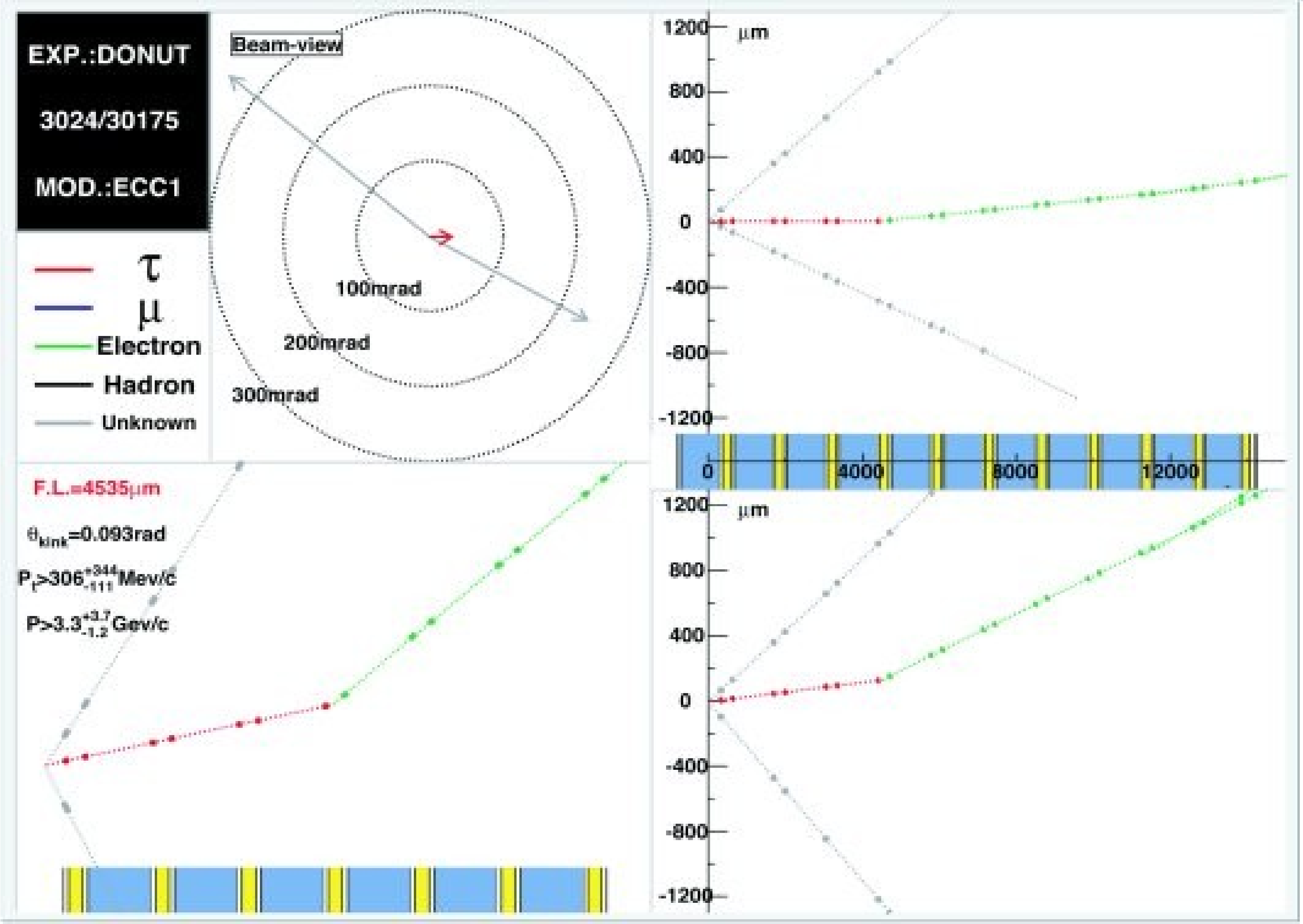
The First Neutrino



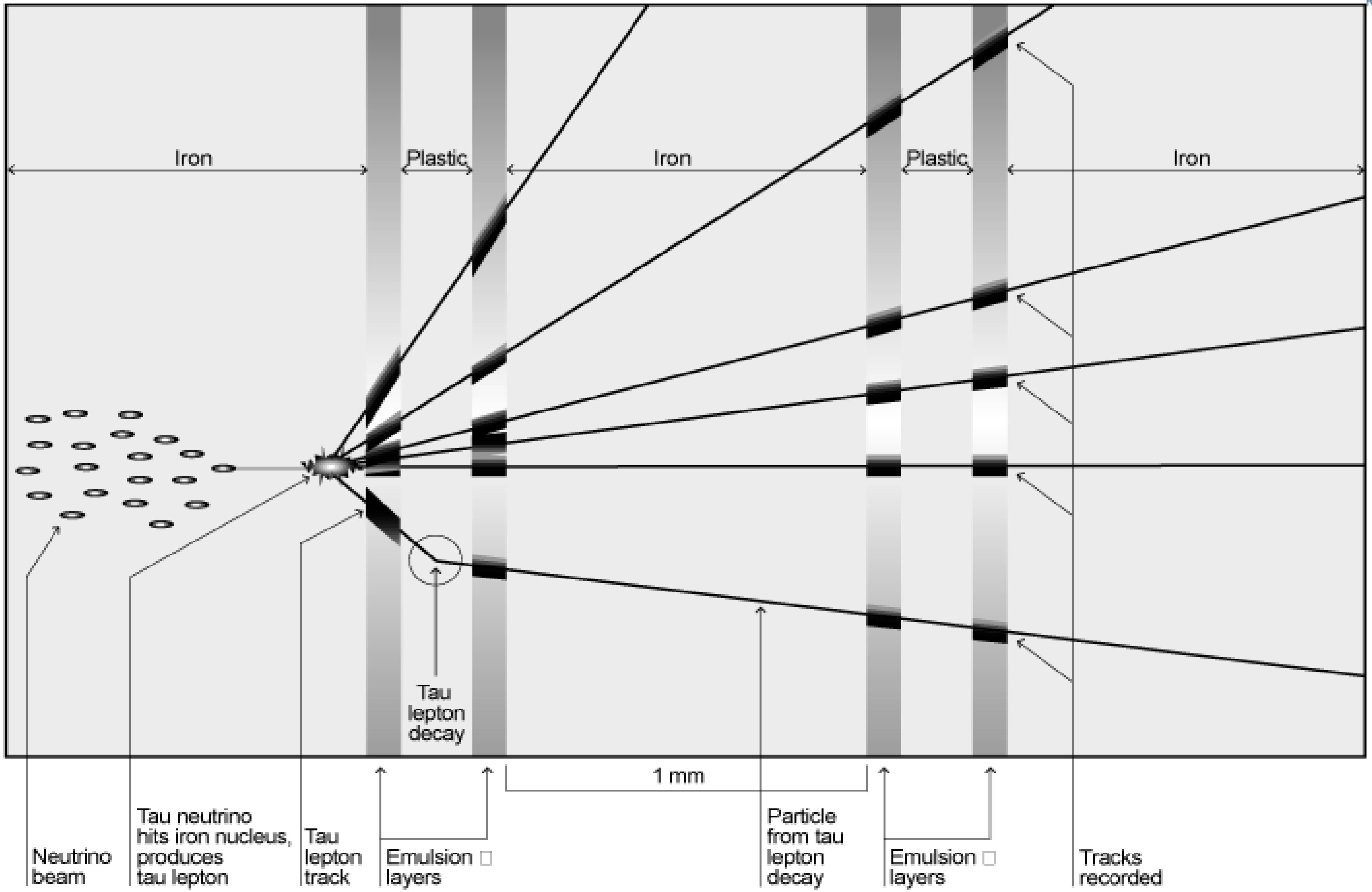
The second neutrino



First ν_τ

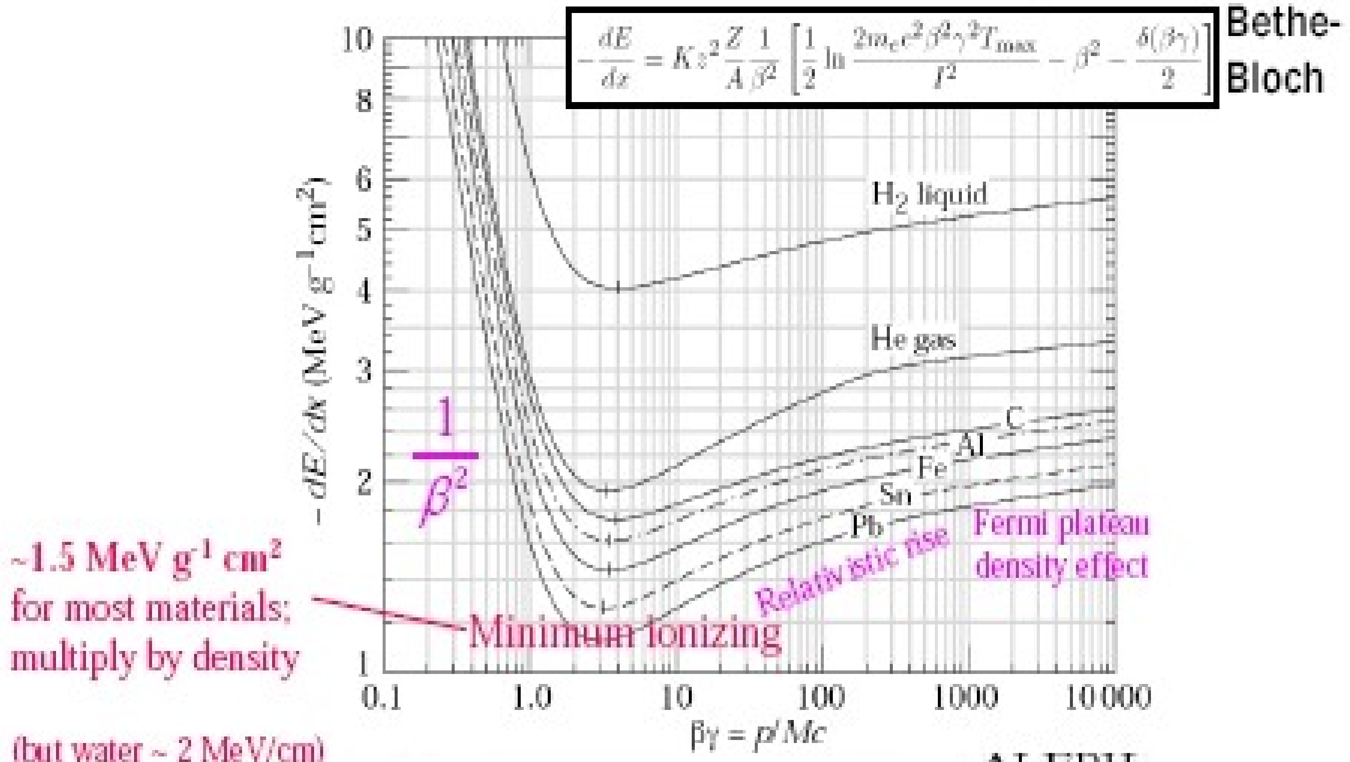

EXP.:DONUT
3024/30175
MOD.:ECC1
τ
μ
Electron
Hadron
Unknown
Beam-view
100mrad
200mrad
300mrad
F.L.=4535μm
θ_{kink}=0.093rad
P_t>306^{+344}_{-111}Mev/c
P>$3.3^{+3.7}_{-1.2}$Gev/c
1200
800
400
0
-400
-800
-1200
μm
0
4000
8000
12000

The Tau Neutrino



Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

dE/dx and Range

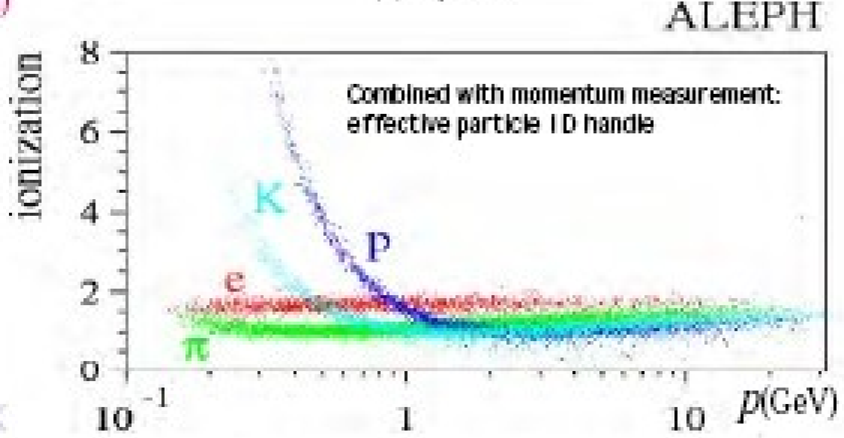


$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Bethe-Bloch

~1.5 MeV g^{-1} cm^2 for most materials; multiply by density

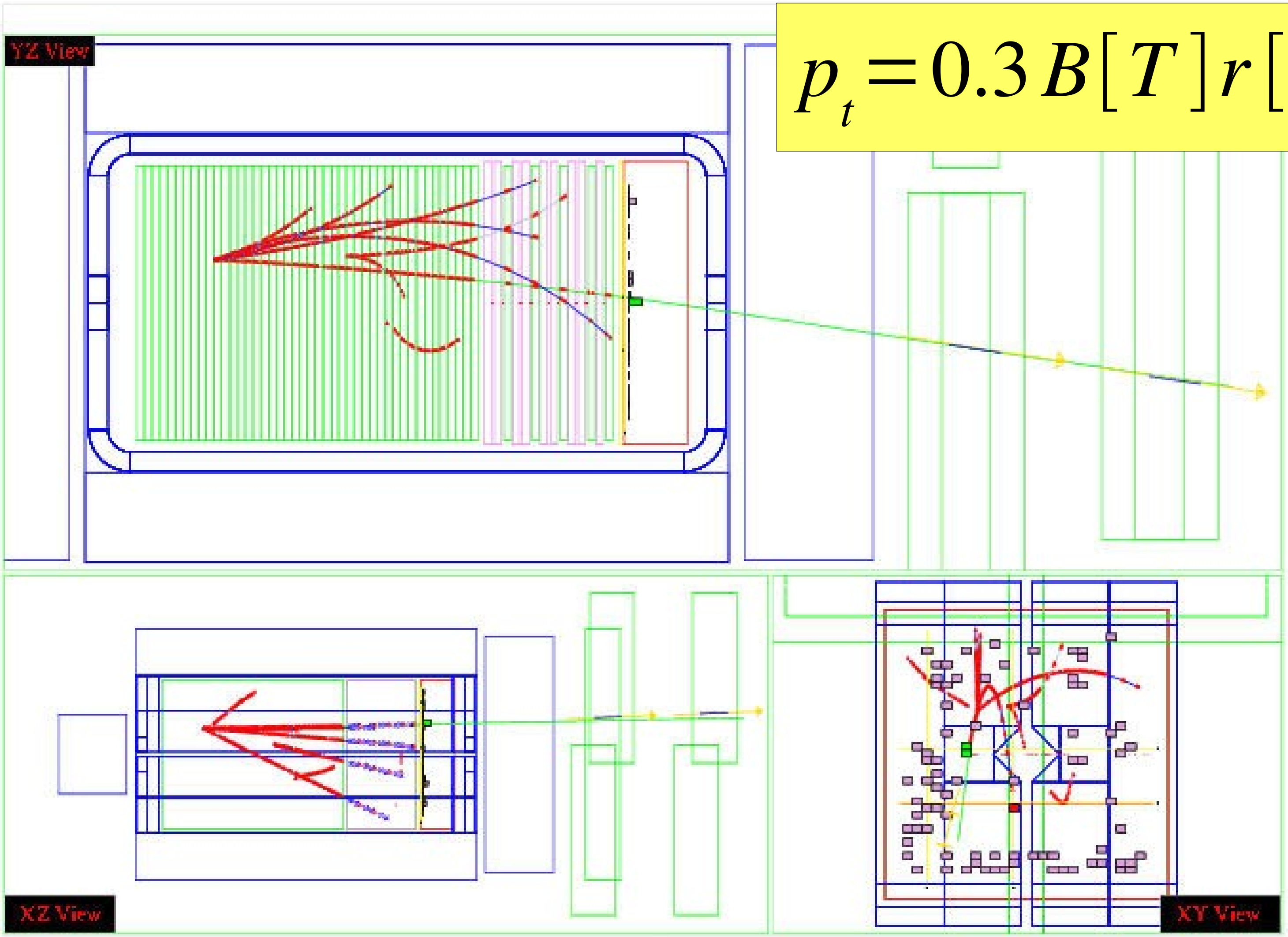
(but water ~ 2 MeV/cm)



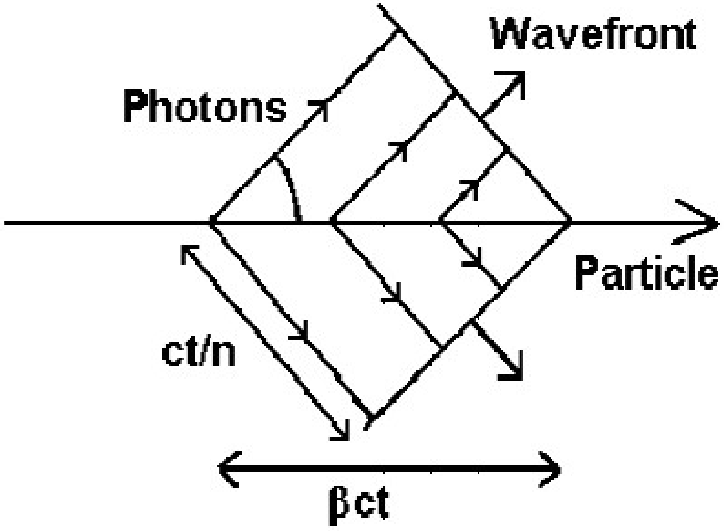
Combined with momentum measurement: effective particle ID handle

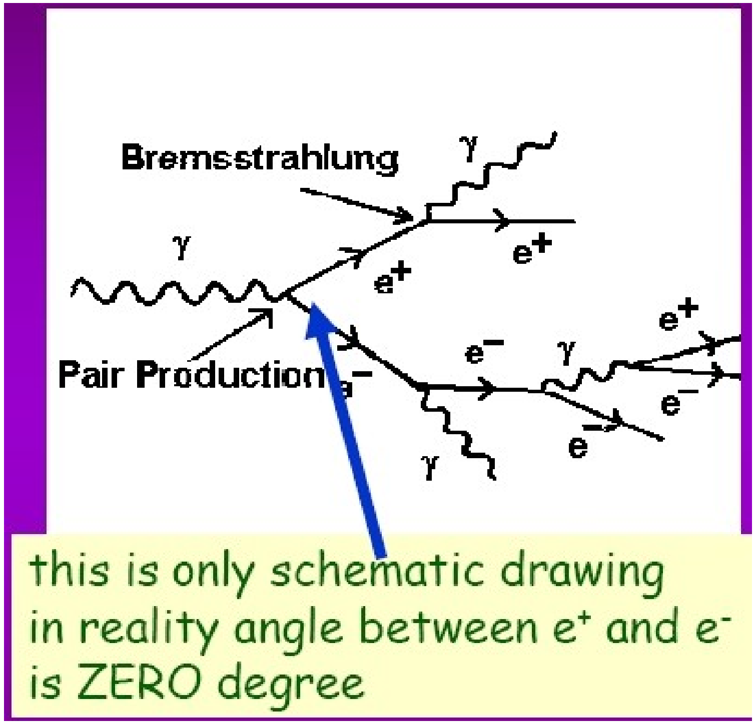
Magnetic Tracking

$$p_t = 0.3\,B[T]\,r[m]$$



Muons vs Photons





this is only schematic drawing
in reality angle between e^+ and e^-
is ZERO degree

The secondary photon interactions smear out the edge of Cerenkov cone and provide particle identification as well.

But where is it?

Still no neutrino observed experimentally? Why?
Bethe-Peierls (1934) provided some of the answer.

Fermi theory predicted cross section for ν p

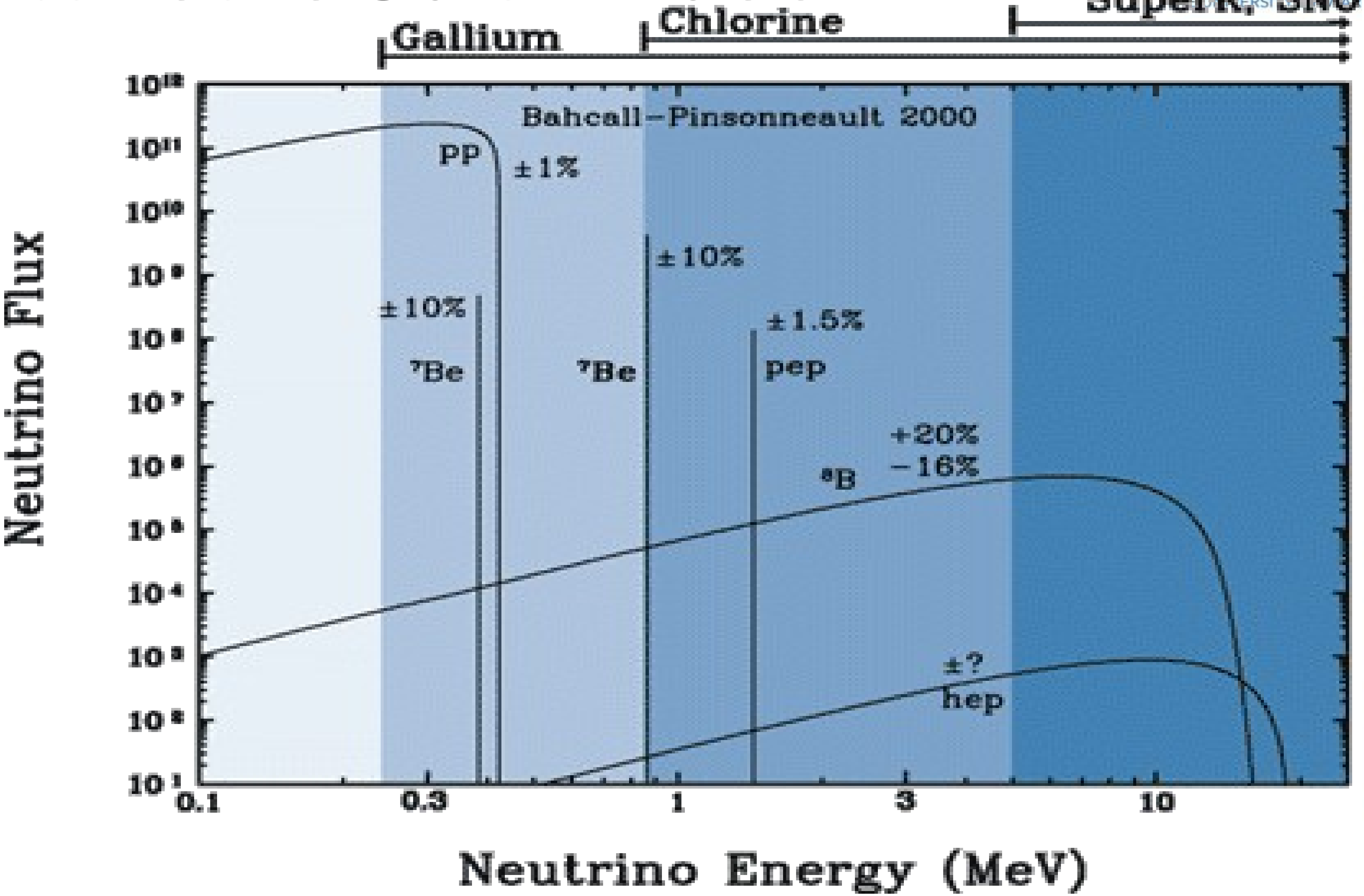
$\sigma \sim 10^{-44}$ cm^2 for 2 MeV ν

$$\lambda_{lead} \sim \frac{1}{N_A \rho \sigma} = \frac{1}{6.10^{23}(nuc/g) \times 7.9 (g/cm^2) \times 10^{-44} (cm^2)}$$

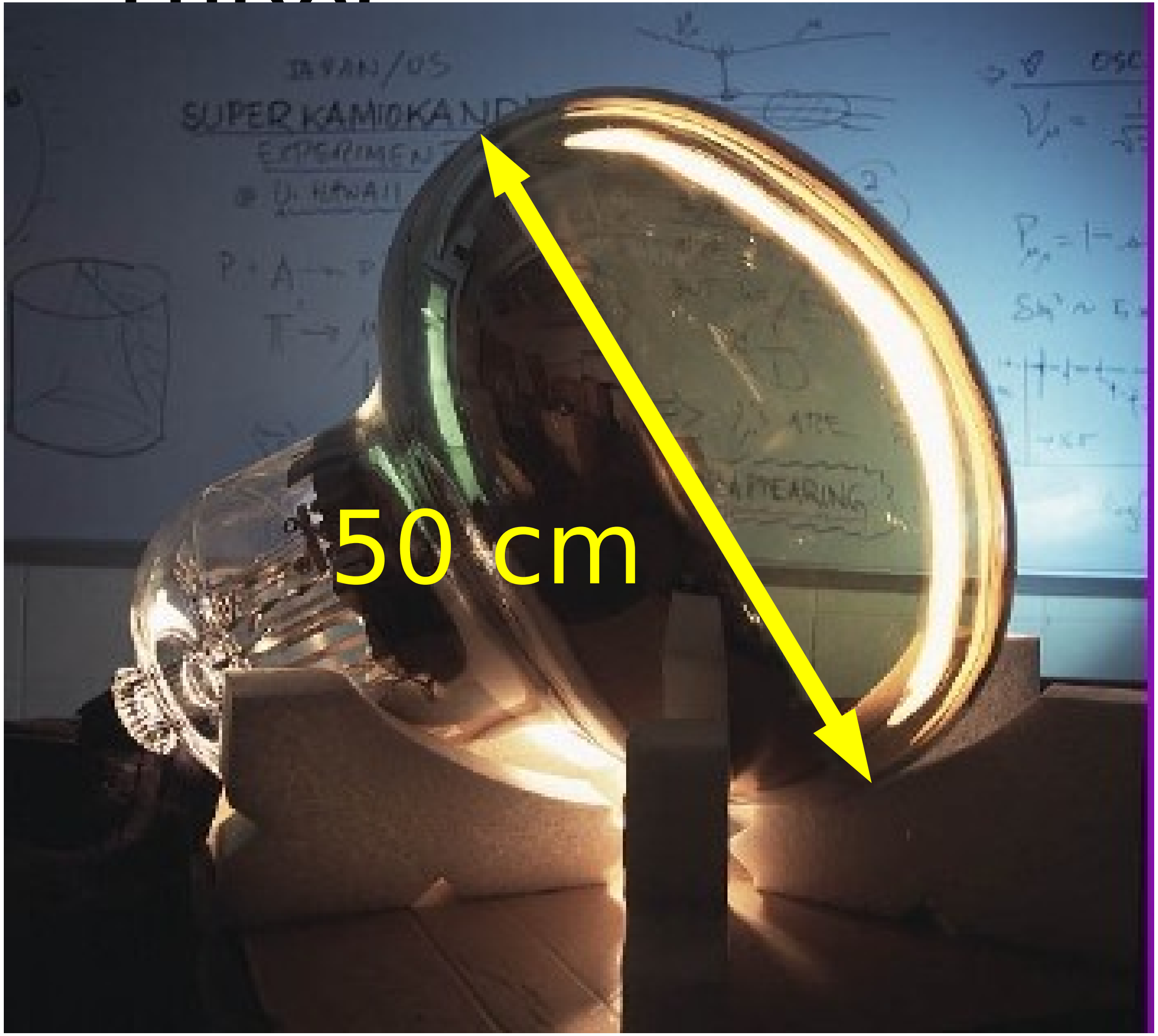
$\lambda_{lead} \approx$ 22 light years

Need a *really* intense source of neutrinos AND very massive detector to detect neutrinos.

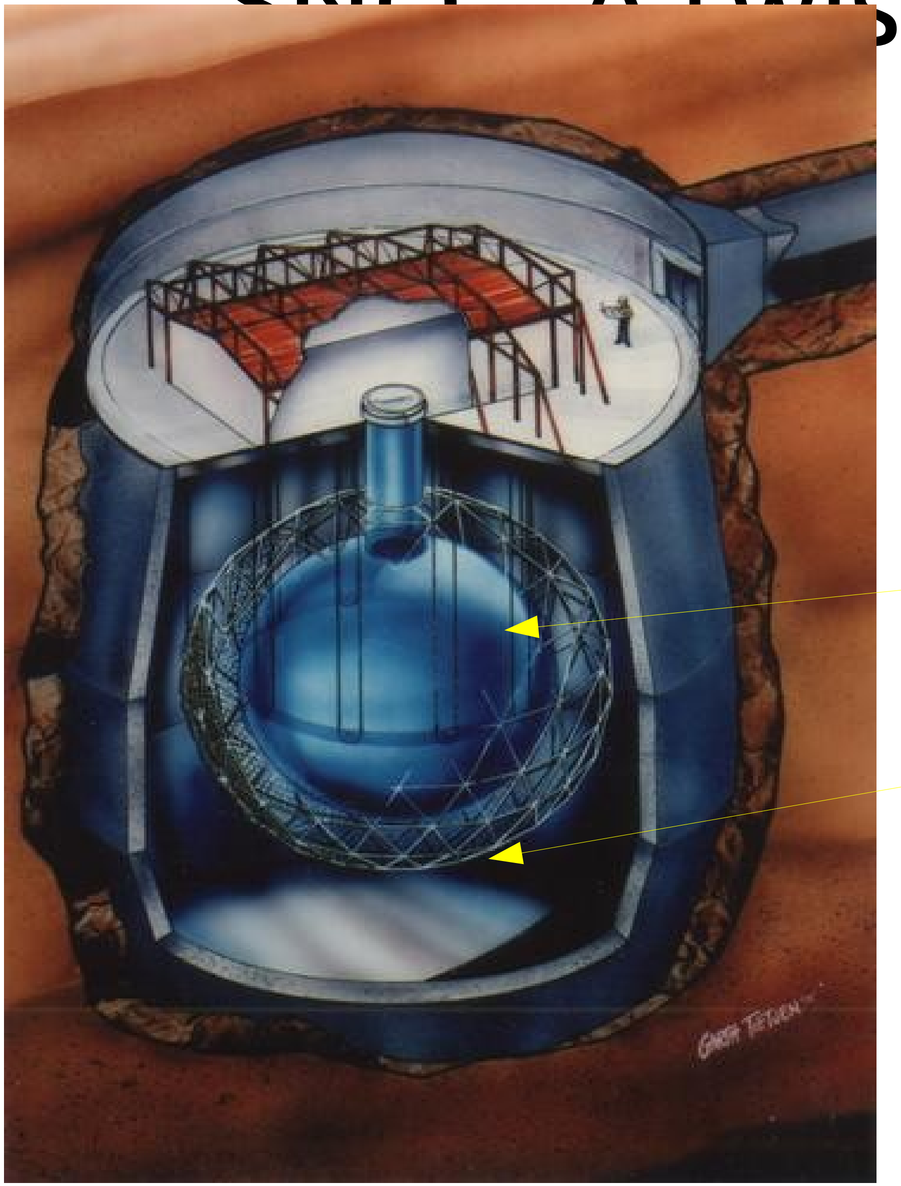
Standard Solar Model

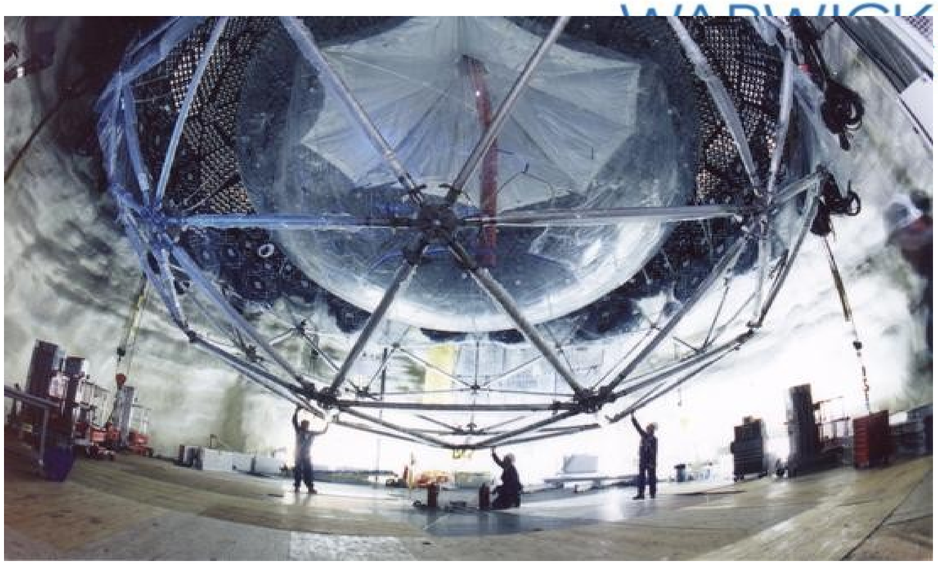


Photomultiplier Tubes



SNO – A twist





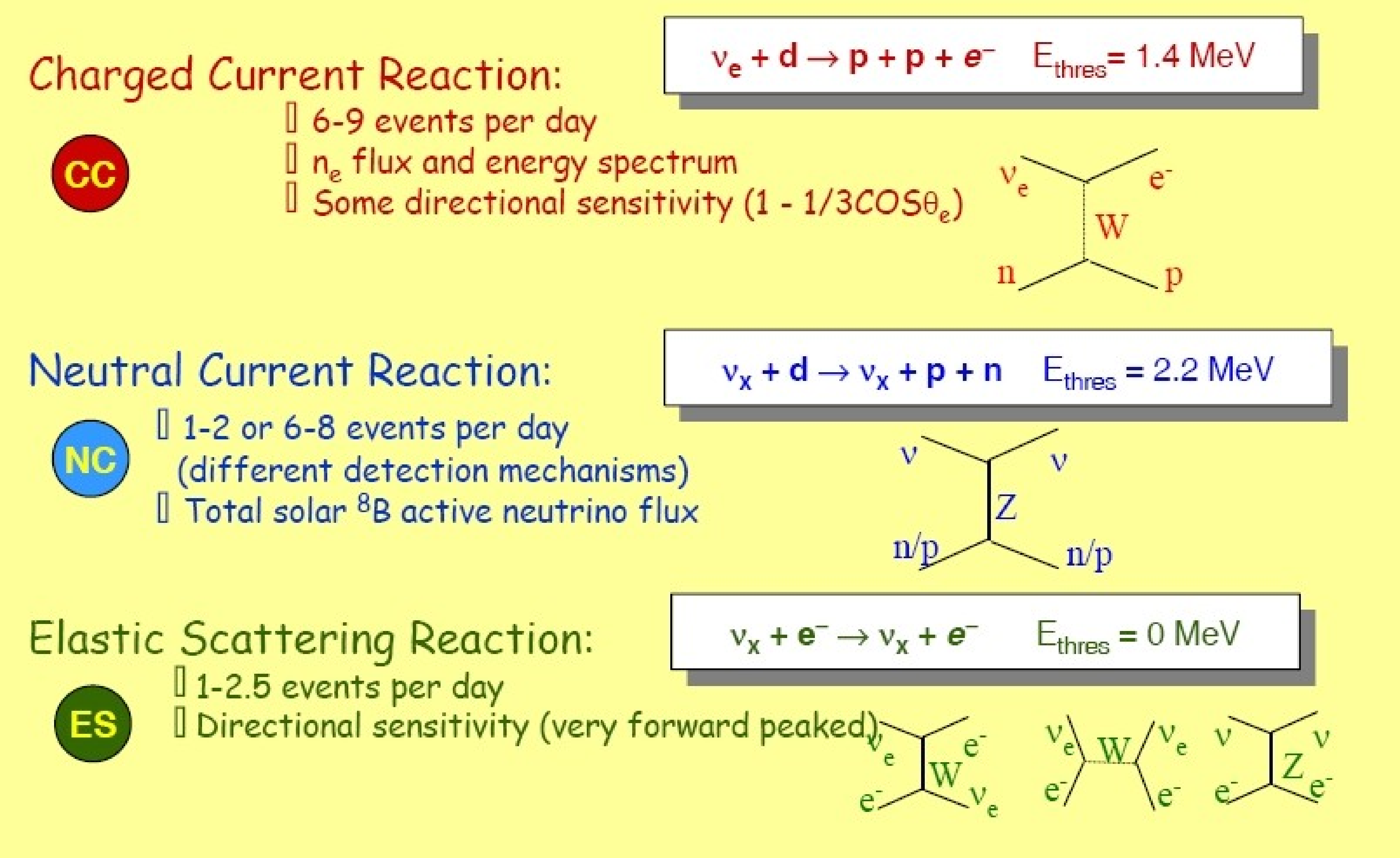
1000 tonnes of D_20

6500 tons of H_20

Viewed by 10,000 PMTS

In a salt mine 2km underground in Sudbury, Canada

ν Reactions in SNO



Charged Current Reaction:

$\nu_e + d \rightarrow p + p + e^-$ $E_{thres} = 1.4$ MeV

CC

- 6-9 events per day
- n_e flux and energy spectrum
- Some directional sensitivity (1 - 1/3COSθ$_e$)

Neutral Current Reaction:

$\nu_x + d \rightarrow \nu_x + p + n$ $E_{thres} = 2.2$ MeV

NC

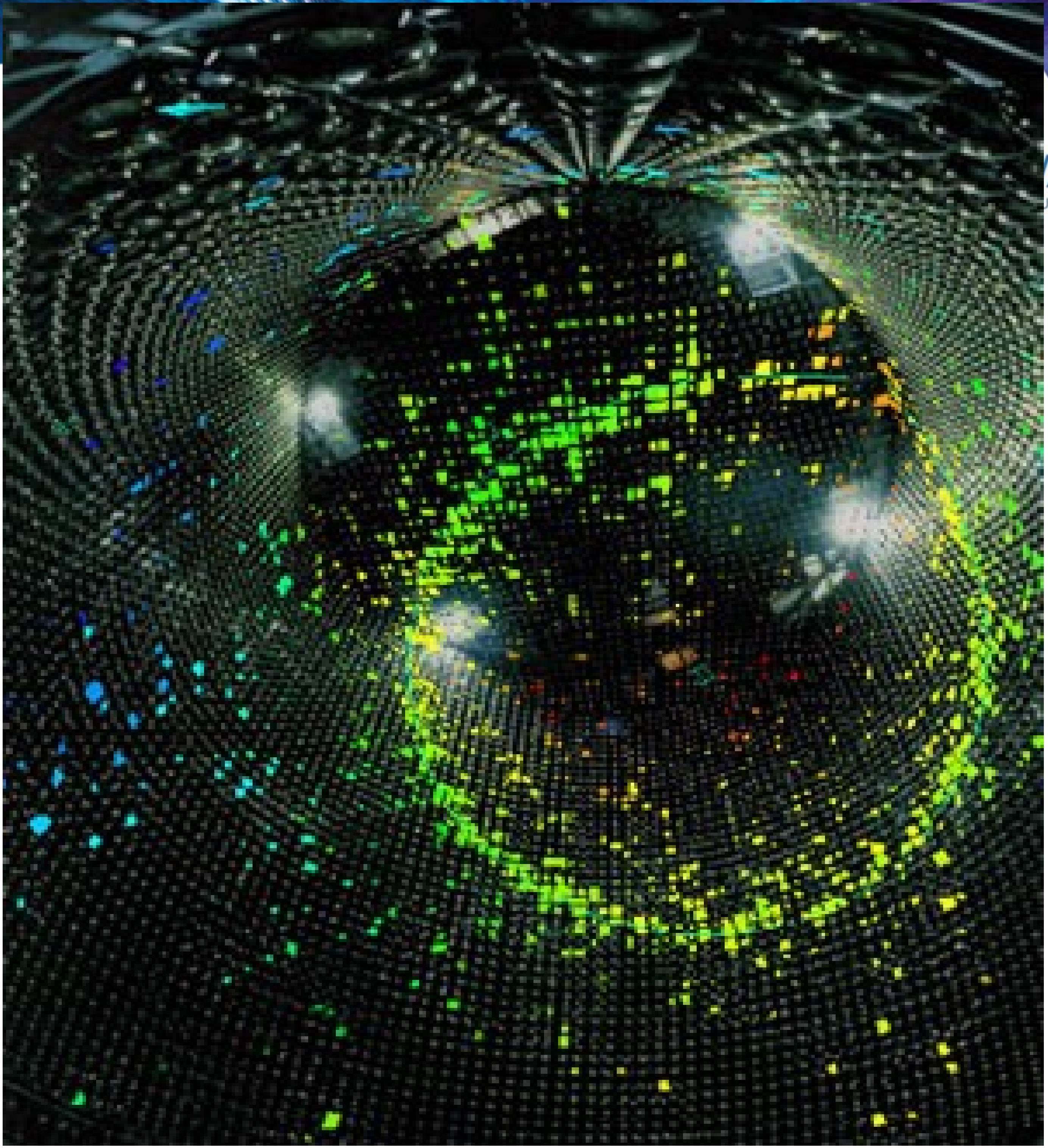
- 1-2 or 6-8 events per day (different detection mechanisms)
- Total solar ^{8}B active neutrino flux

Elastic Scattering Reaction:

$\nu_x + e^- \rightarrow \nu_x + e^-$ $E_{thres} = 0$ MeV

ES

- 1-2.5 events per day
- Directional sensitivity (very forward peaked)

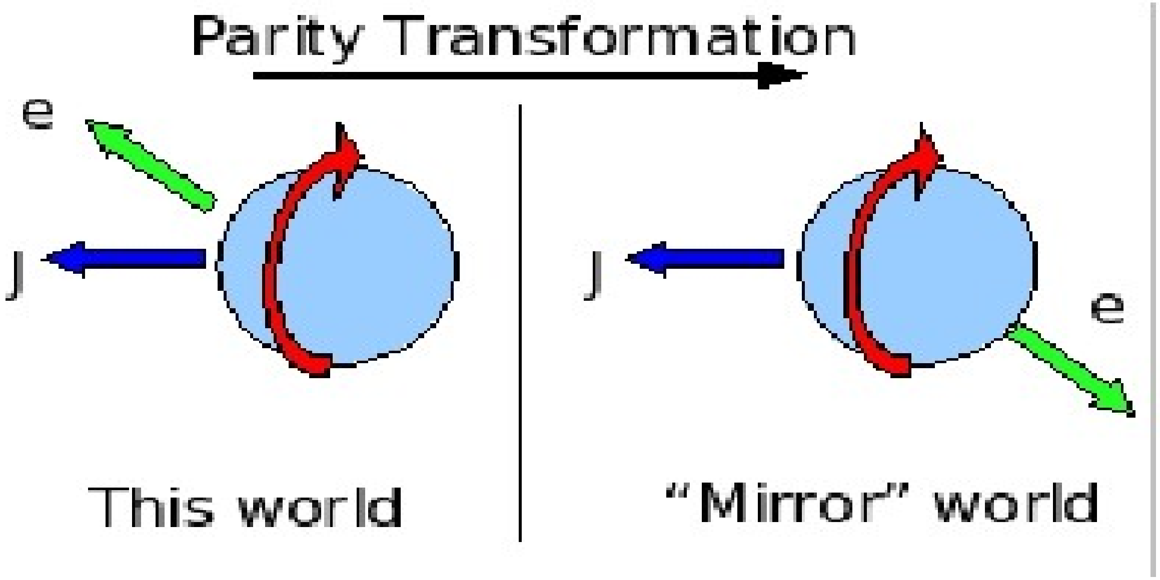


Neutrino Detectors

- No neutrino colliders – detector IS the target
- Low cross section implies large mass
- Neutrinos interact everywhere – vertex can be anywhere
- Identification of charge lepton to separate NC and CC
- Measurement of energy and scattering angle of charged lepton
- Measurement of total hadronic energy
- Identification of single hadrons for hadronic studies
- Use of different target materials (nuclear effects)

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

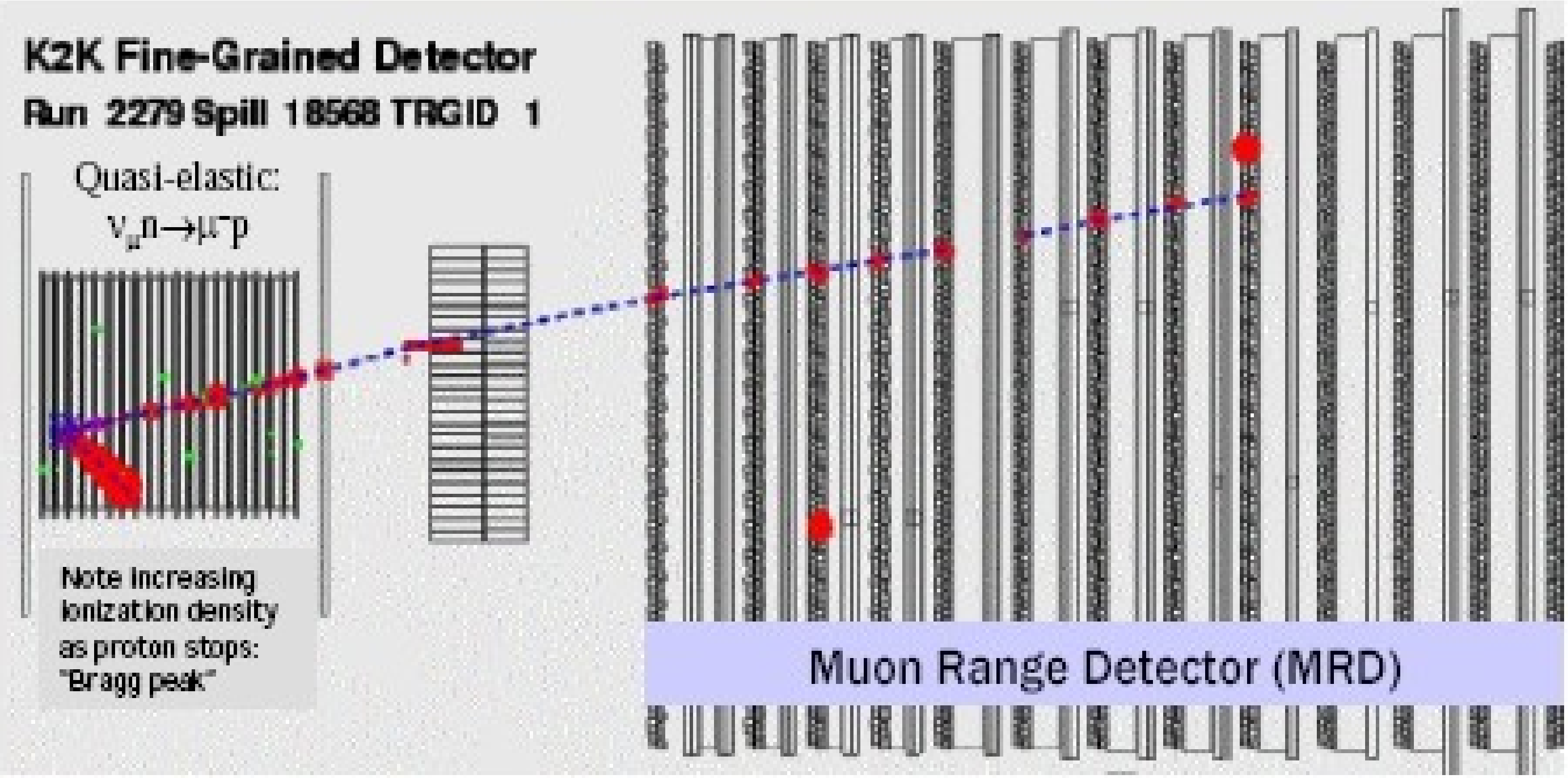
Weak Interaction



P(world) = P(mirror) if parity conserved
So electron must be emitted isotropically

It isn't. In fact it's emitted along only one direction so parity is maximally violated. That is the weak interaction only couples left-handed (chiral) particles

Simple, no magnetic field; limited by size.
Reconstructed energy: build range table, integrating Bethe-Bloch; incorporate each layer of differing material.(ask GEANT for help)



Note increasing ionization density as proton stops: "Bragg peak"

$dE/dx)_{Fe} = 1.45\ \mathrm{MeV\ g^{-1}cm^{2}} \times 7.9\ \mathrm{gm\ cm^{-3}} = 90\ \mathrm{MeV/cm}$ … 1 GeV muon travels ~ 1m

(careful use of range chart, eg. in PDG, gives 80 cm)

NuTeV Fit

$$\sin^2\theta_W^{(on-shell)} = 0.2277 \pm \pm 0.0013(stat.) \pm 0.0009(syst.)$$

$$= 0.2277 \pm 0.0016$$

(Previous neutrino measurements gave 0.2277 ± 0.0036)

- Standard model fit (LEPEWWG): 0.2227 ± 0.00037

A 3σ discrepancy ....

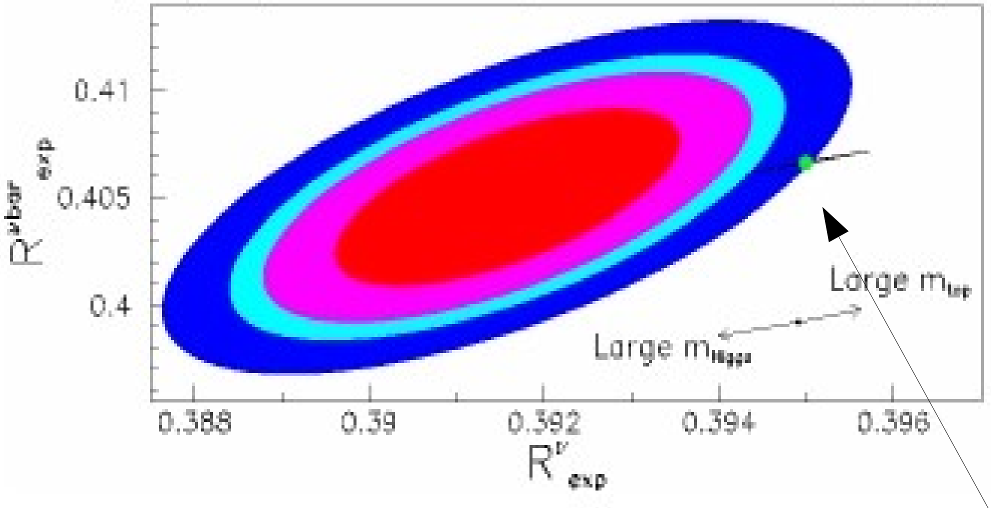
$R^{\nu}_{\exp} = 0.3916 \pm 0.0013$

$(SM: 0.3950) \quad \Leftarrow 3\sigma\ difference$

$R^{\bar{\nu}}_{\exp} = 0.4050 \pm 0.0027$

$(SM: 0.4066) \quad \Leftarrow Good\ agreement$

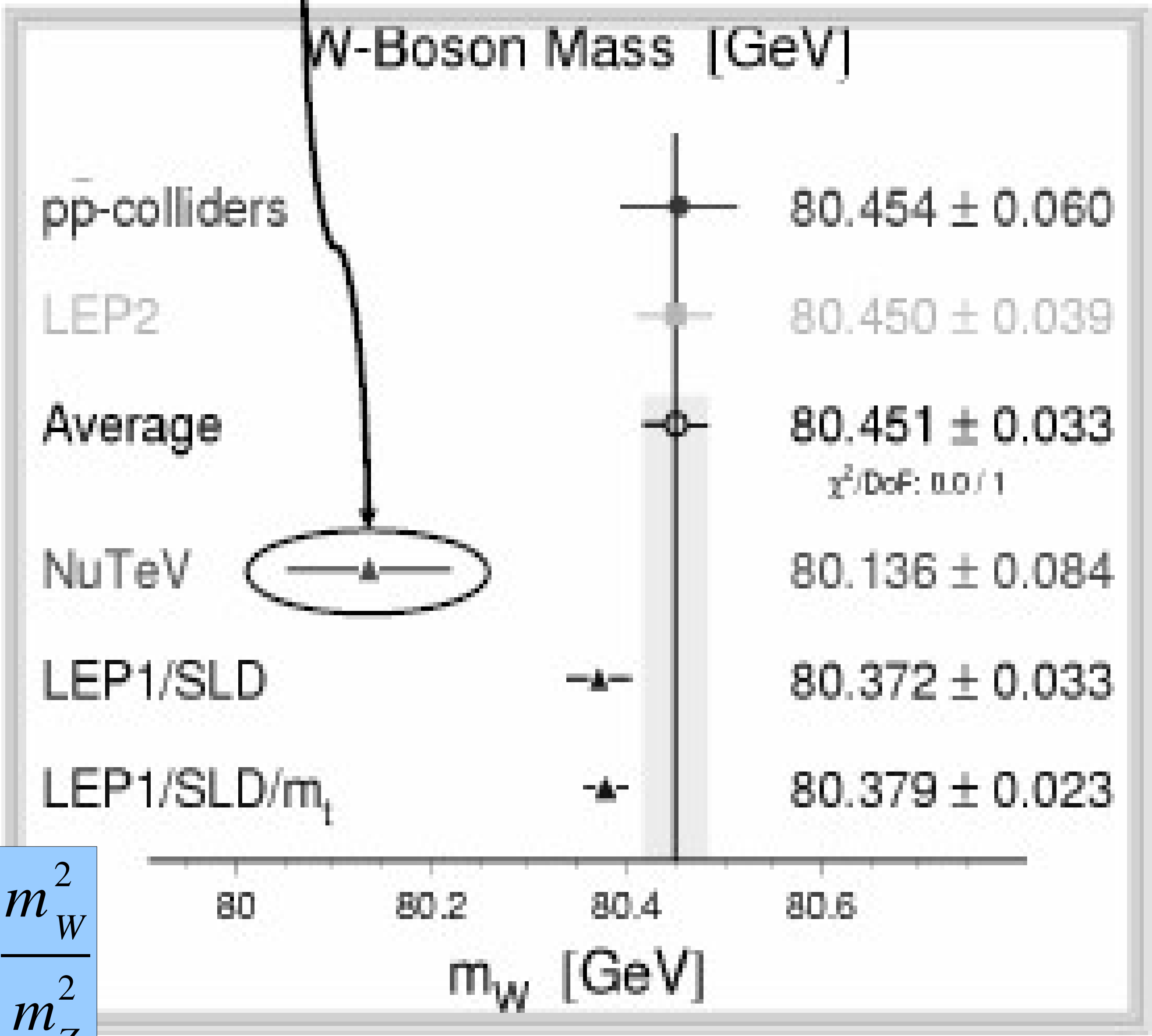
68%,90%,95%,99% C.L. Contours, Grid of SM ± 1σ mtop, m_{Higgs}



Standard Model measurement

$$R^{\nu} = \frac{\sigma_{NC}(\nu N)}{\sigma_{CC}(\nu N)}; R^{\bar{\nu}} = \frac{\sigma_{NC}(\bar{\nu} N)}{\sigma_{CC}(\bar{\nu} N)}$$

Incidentally - A Puzzle



$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

Possible interpretations

- *New Beyond-Standard-Model physics?*
  - Difficult to find something which does this just for ν
- *Purely experimental*
  - Multiple checks. Not obvious if it is.
- *Mundane explanations*
  - Charm mass effects
  - Radiative effects
  - *Isospin symmetry violation :* $u_p(x) \neq d_n(x)$
  - Strange/anti-Strange sea asymmetry : $\int s(x) \neq \int \bar{s}(x)$ (intrinsic strangeness?)
  - *Different nuclear effects for NC over CC (Z over W)*

Fermi Operators

$$H=\sum_i C_i \int d^3x (\overline{\psi_p}\Gamma_i\psi_n)(\overline{\psi_e}\Gamma_i\psi_\nu)$$

General LI Operator : $\Gamma_i \in 1, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}$

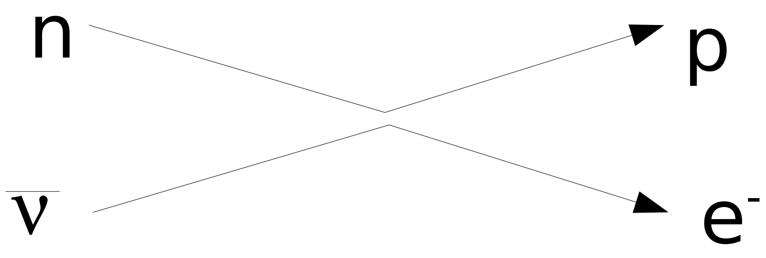
	Γ_i	Parity
S	1	1
V	γ_μ	(+,-,-,-)
T	$\sigma_{\mu\nu}$	
AV	$\gamma_\mu\gamma_5$	(+,+,+,+)
PS	γ_5	-1

Mixture which maximally violates parity is found to be

$$\boxed{\Gamma_i=\gamma_i(1-\gamma_5)}$$

V-A coupling

Fermi Couplings



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

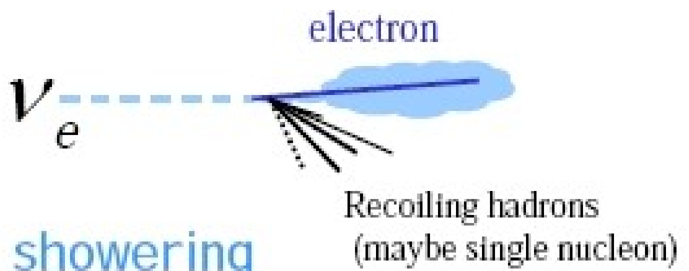
$$\Downarrow$$

$$L \propto G_F[\bar{\phi}_p(x)\boxed{\gamma^\mu(g_V - g_A\gamma_5)}\phi_n(x)][\bar{\phi}_e(x)\boxed{\gamma_\mu(1-\gamma_5)}\phi_\nu(x)]$$

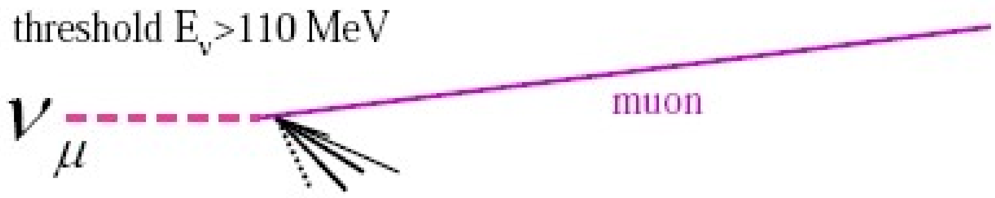
V-A interaction

An intrinsic property of the Weak Interaction

Neutrino Flavour



showering



penetrating

challenging

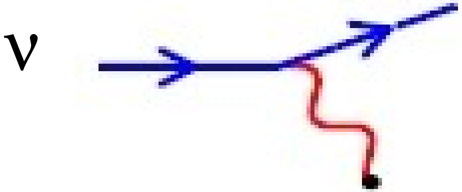
annoying (frequently background)

τ	$\rightarrow e\nu\nu$	18%
	$\rightarrow \mu\nu\nu$	18%
	$\rightarrow 3\pi\nu$	14%
	$\rightarrow \pi\nu$	11%

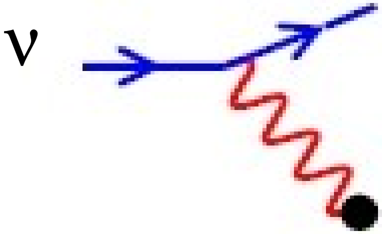
In which neutrinos reluctantly interact

A neutrino can see….

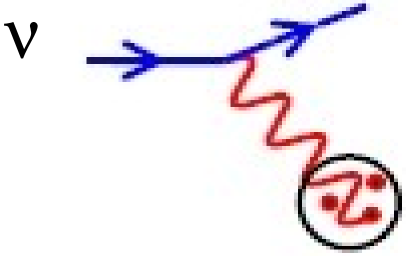
- Very low Q^2, $\lambda > r_p$, and scattering is off a “point-like” particle



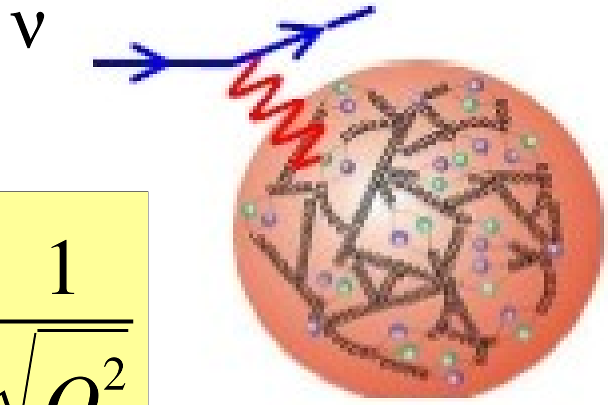
- Low Q^2, $\lambda \sim r_p$, scattering is off an extended object



- 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

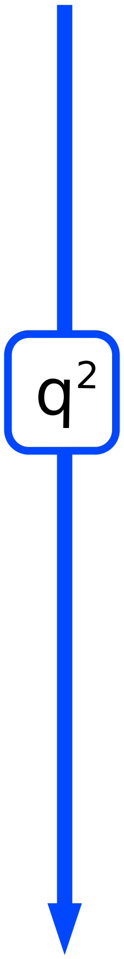


$$\lambda = \frac{1}{p} \sim \frac{1}{\sqrt{Q^2}}$$

Neutrino-Nucleon Interactions

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
  - ν_μ + quark → μ^- + quark'



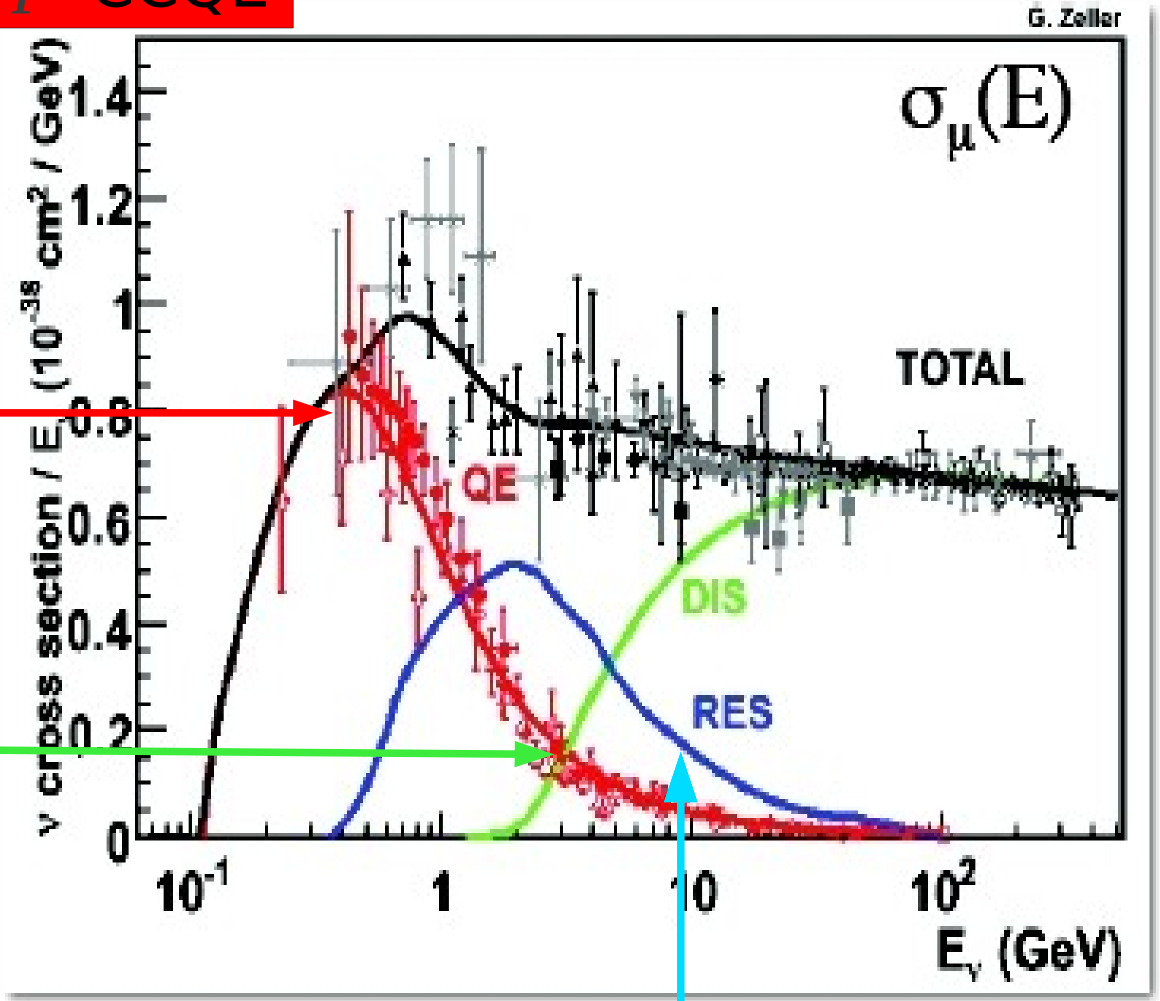
NC – Z^0 exchange

- 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
  - ν_μ + quark → ν_μ + quark

Cross-sections – current knowledge

ν_μ

$\nu_\mu + n \rightarrow \mu^- + p$ CCQE



“Transition Region”

$\nu_\mu + N \rightarrow \mu^- + N' + \pi$ Single pion

CCQE - Experimental signature

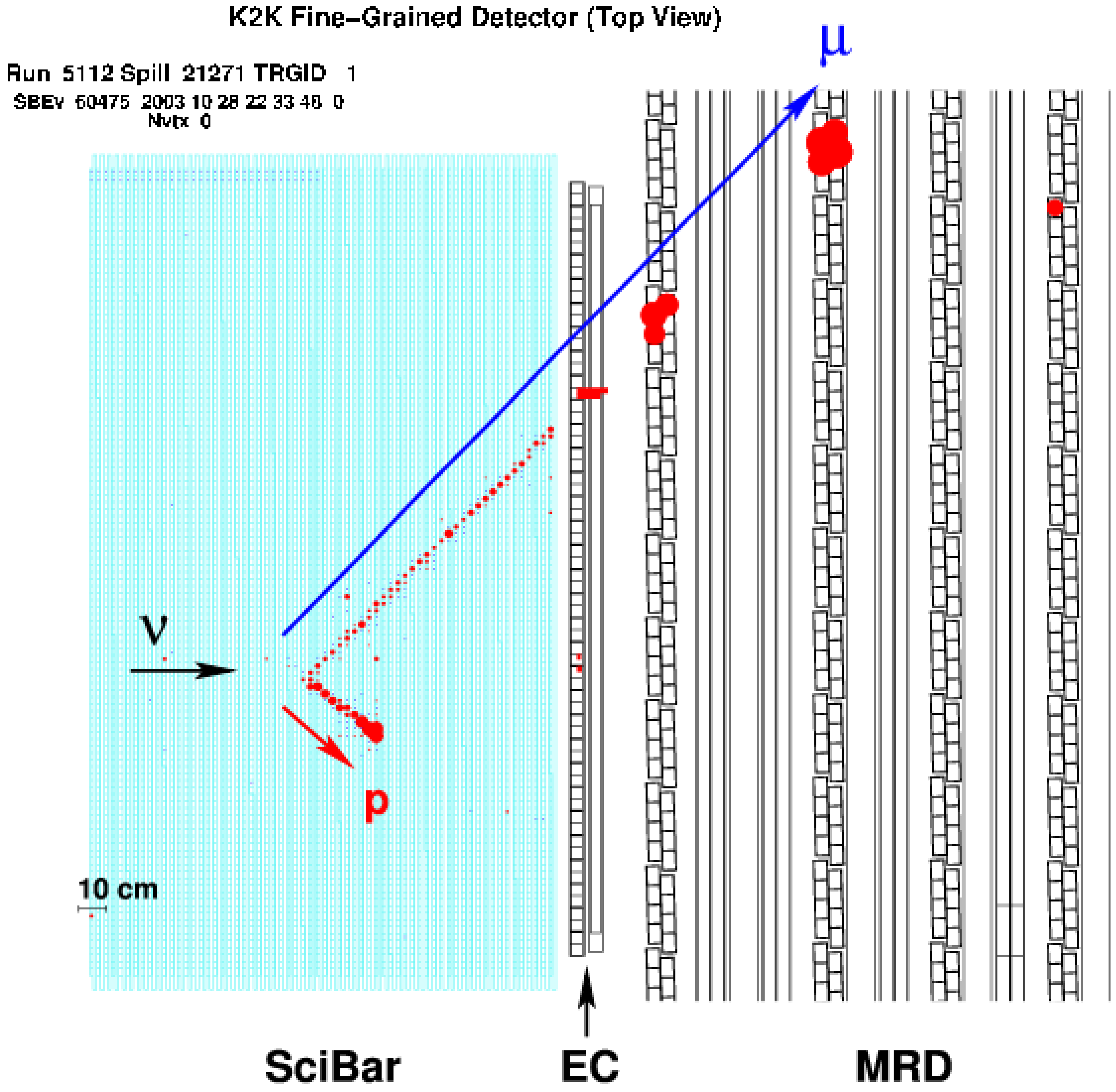
$$\boxed{\nu_\mu + n \rightarrow \mu^- + p}$$

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

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

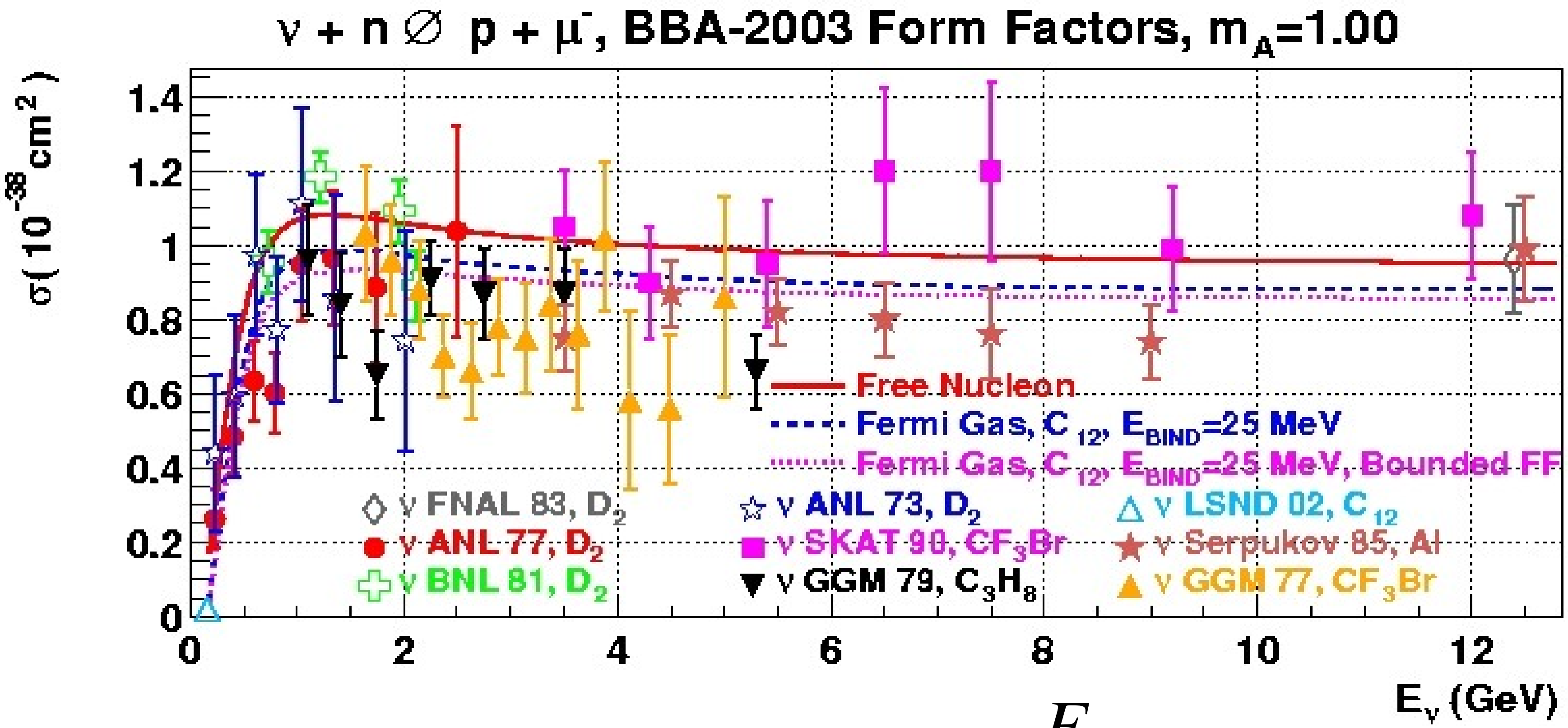
Proton id from dE/dx
Muon id from range
Two-body so angles are known if E_μ is known

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



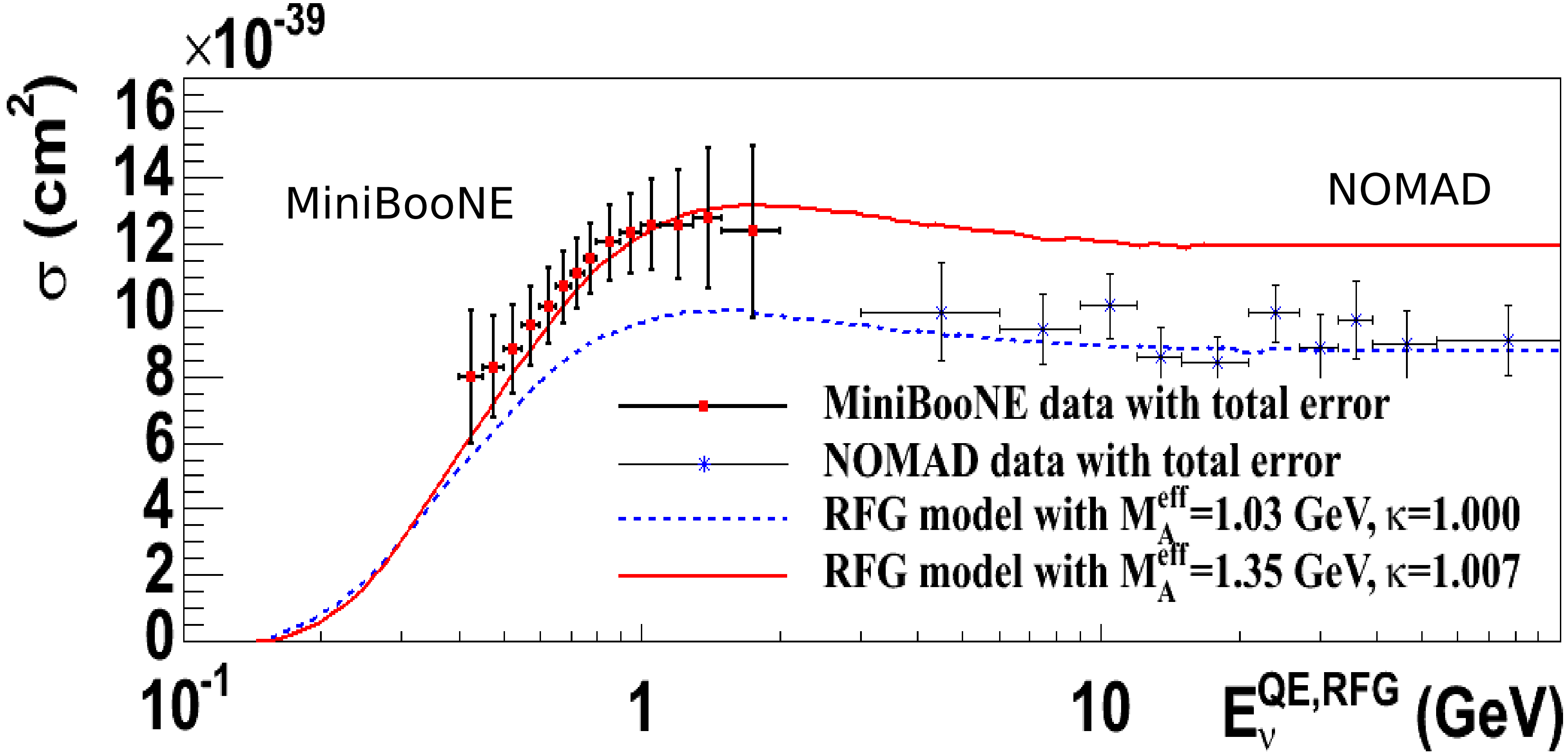
Problems with QE

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



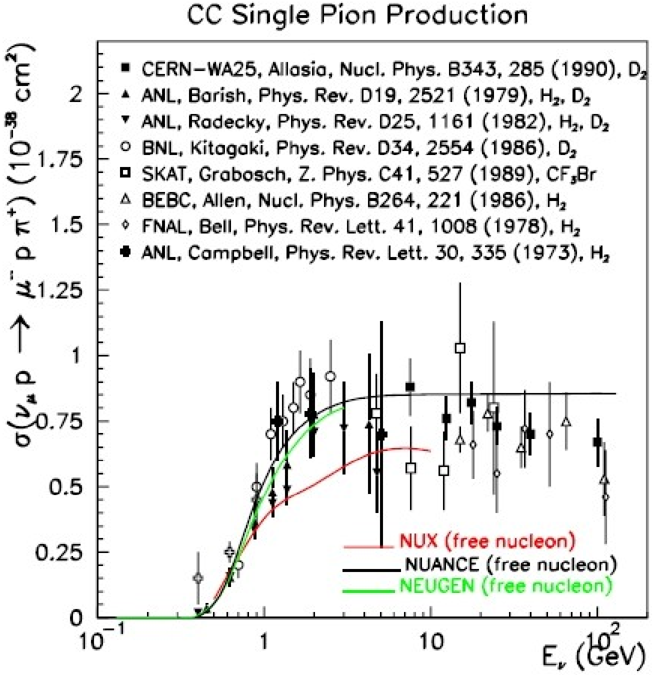
Note tension between low and high energy measurements

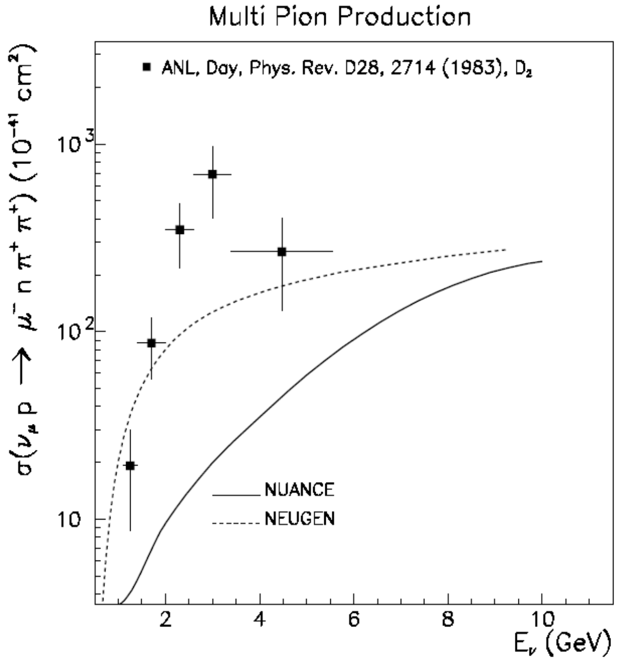
Both on carbon target

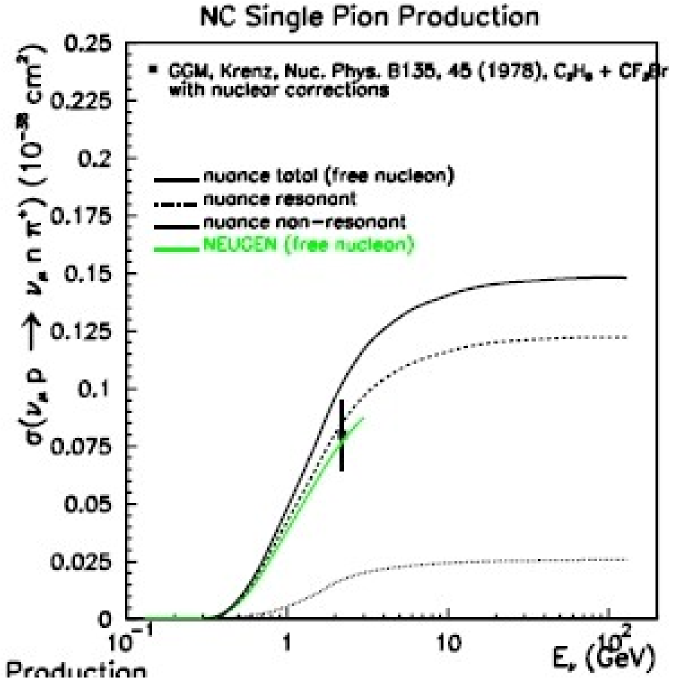
Y. Nakajima *NuInt11*

Resonance Region

The data is impressively imprecise


CC Single Pion Production


Multi Pion Production

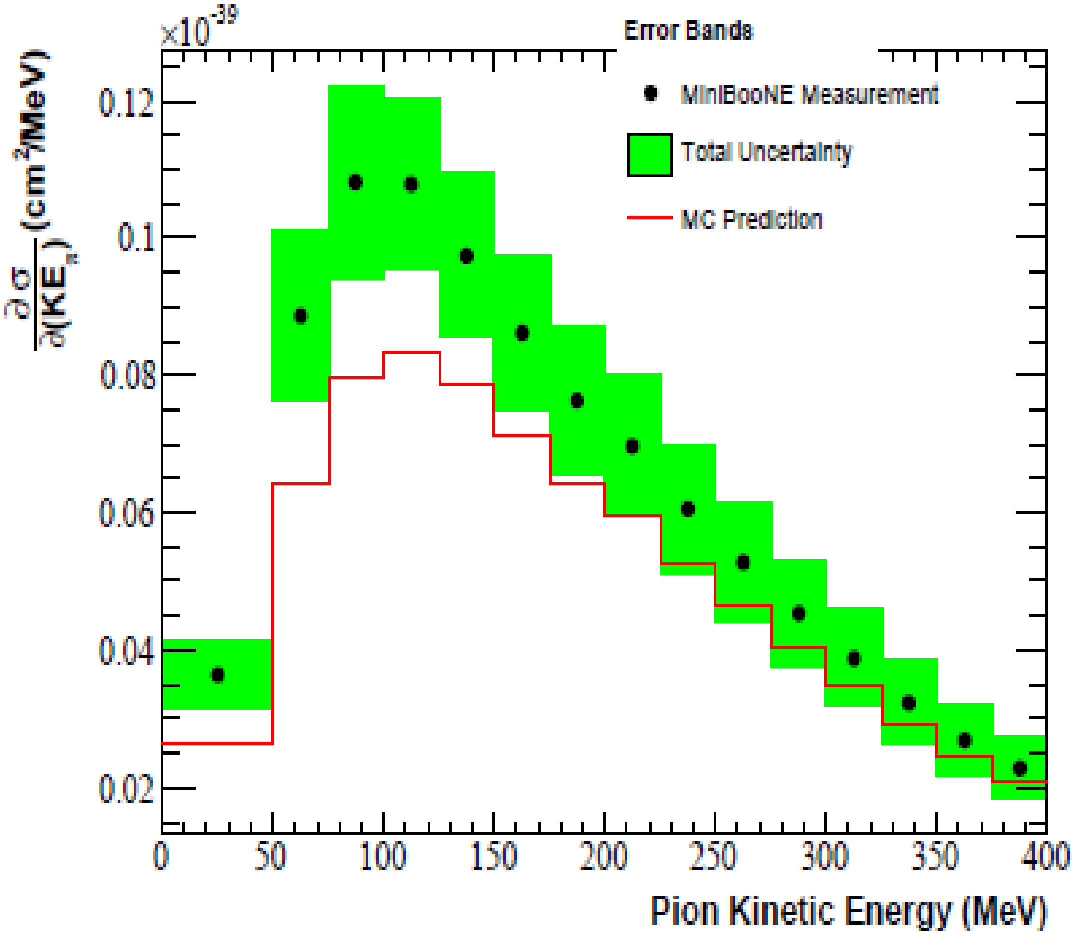

NC Single Pion Production

$$\nu_\mu p \to \mu^- p \pi^+ \qquad \nu_\mu p \to \mu^- n \pi^+ \pi^+ \qquad \nu_\mu p \to \nu_\mu n \pi^+$$

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

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

Sort-of getting better



MiniBooNE

- Cross section for CC ν interactions producing a single π exiting the nucleus
- Data from NOMAD, SciBooNE, T2K & K2K also available or becoming available

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

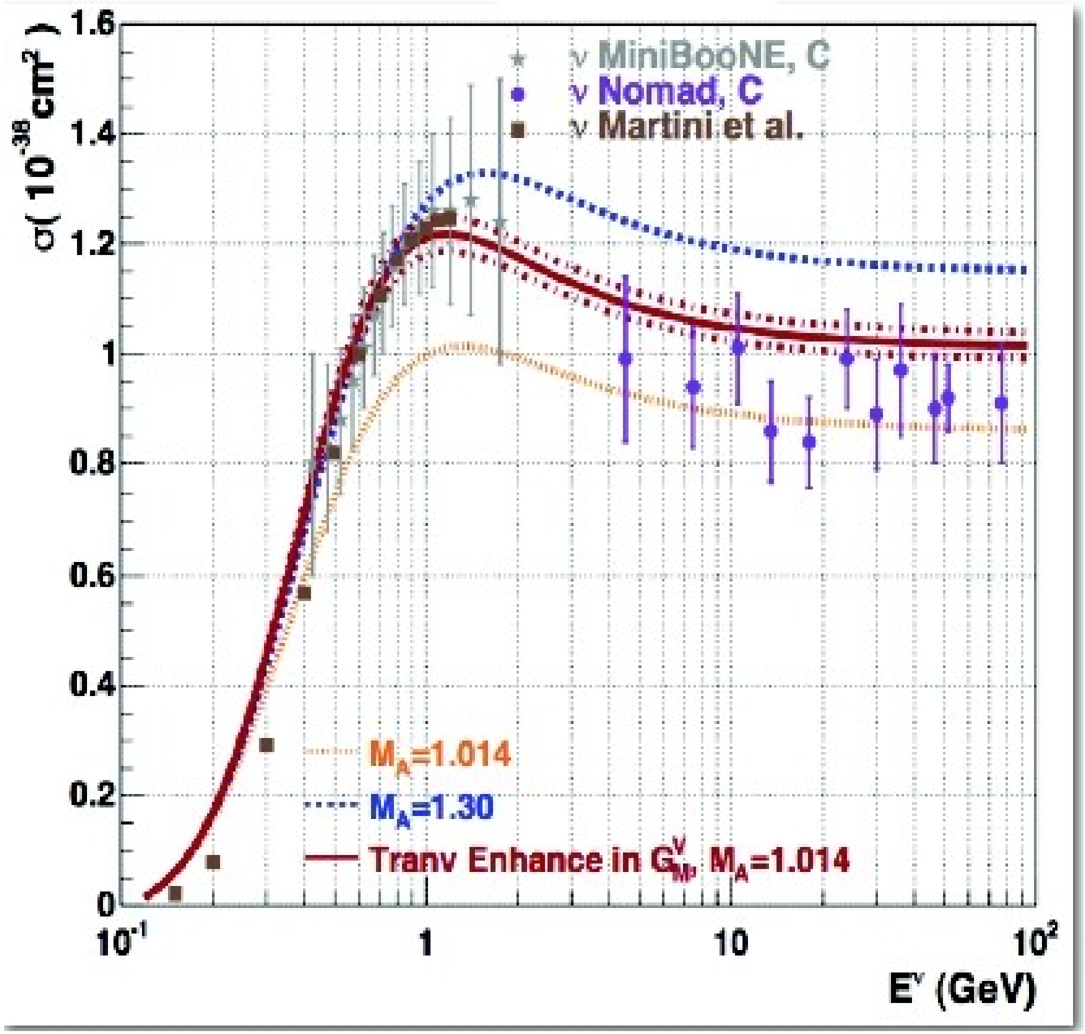
2. The outgoing final state can interact with the target nucleus.

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

Theoretical uncertainties are **large**

- At least 15%
- If precise knowledge is needed for a particular target (e.g. Water, hydrocarbon) then measurements are needed
- Last measurements taken in the '70s

CCQE and Nuclear Effects



Bare interaction

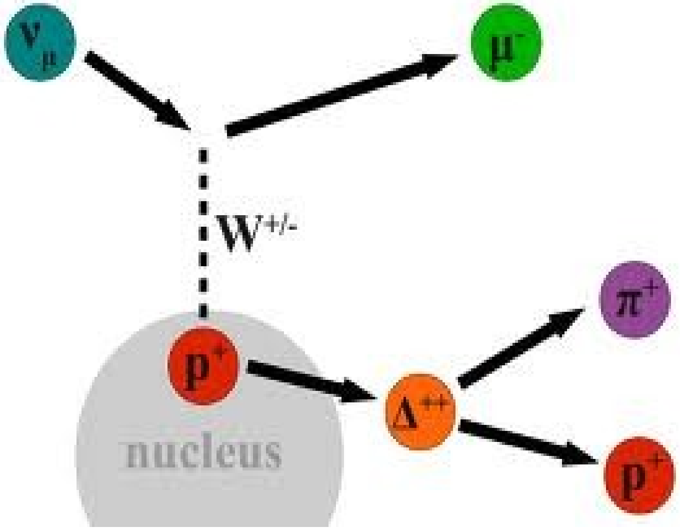
$$\nu_\mu + n \rightarrow \mu + p$$

Nucleon-correlations

Low Q2 probe can be shared by neighbouring nucleons in nuclear target

$$\nu_\mu + (n, n) \rightarrow \mu + p + p$$

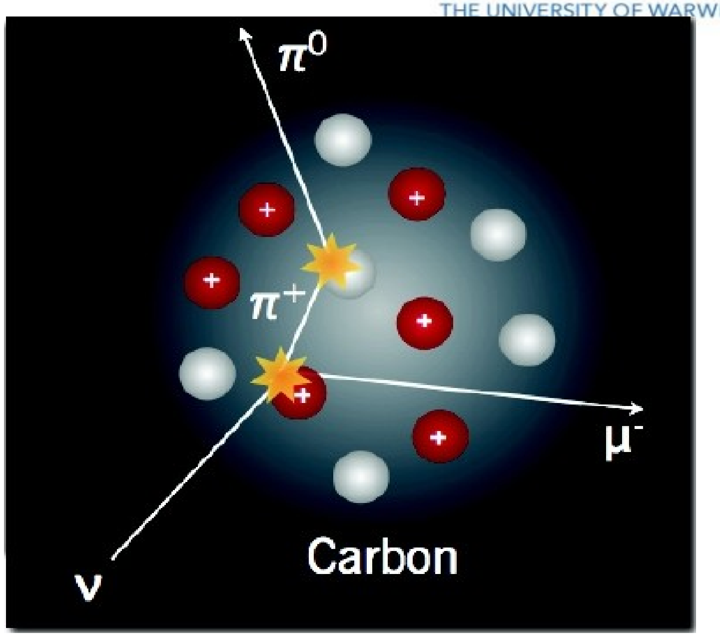
Resonance and Nuclear Effects



Nuclear rescattering

→

Charge exchange

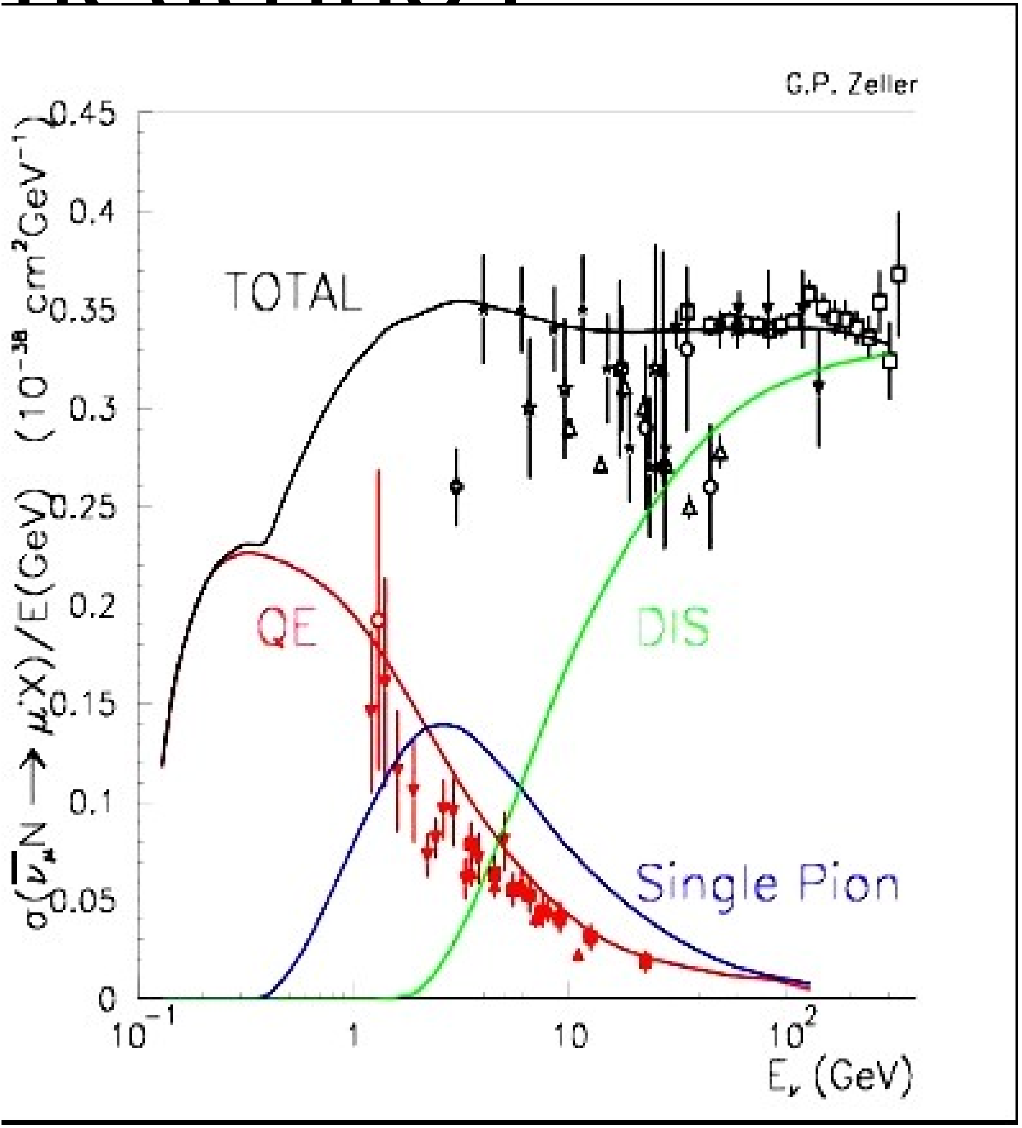


$$\nu_\mu + p \to \Delta^{++} \to \pi^+ + p$$

$$\nu_\mu + p \to \Delta^{++} \to \pi^+ + p \to \pi^0 + p$$

In the past few years neutrino physics has gone from basic tree-level physics to an understanding that (i) nuclear effects are important (ii) we don't know enough about them and (iii) theorists and the electron scattering community can really help here.

World Data for Antineutrinos



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)

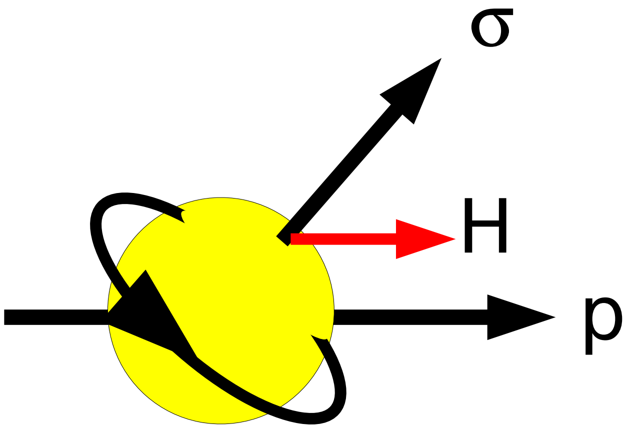
- Weak interaction maximally violates parity in that it only couples to left-handed chiral particles and right-handed chiral antiparticles

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

- This has implications for neutrinos

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

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)

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

- A right-handed chiral neutrino might exist - it just can't couple to any of the forces