Neutrinos

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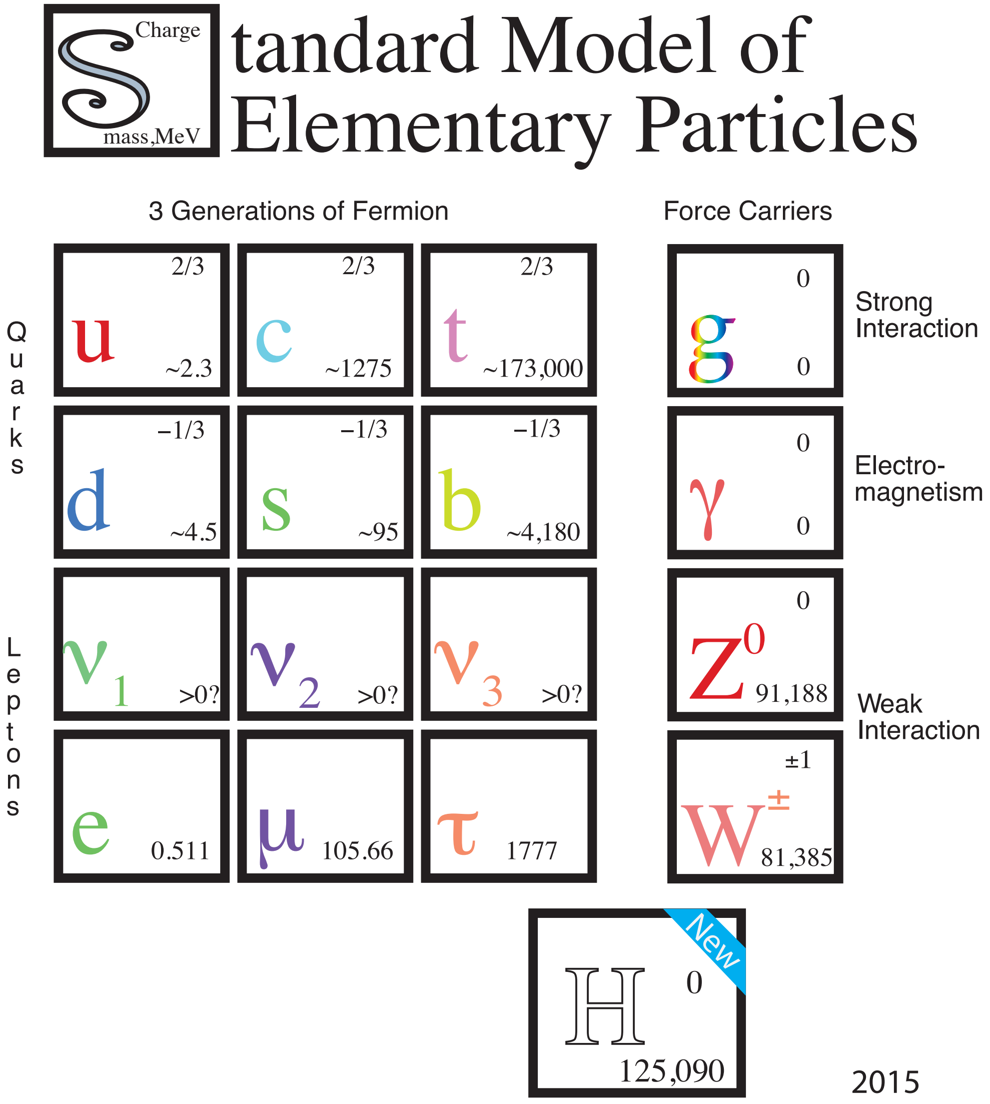
Benasque - September 2016

Outline

- Cast of characters
- Basics of neutrino interactions
- Oscillation Physics
- Other cool neutrino stuff as time permits.



Charge
S
mass,MeV
tandard Model of Elementary Particles
3 Generations of Fermion
Force Carriers
Quarks
u 2/3 ~2.3
c 2/3 ~1275
t 2/3 ~173,000
d −1/3 ~4.5
s −1/3 ~95
b −1/3 ~4,180
Leptons
ν1 >0?
ν2 >0?
ν3 >0?
e 0.511
μ 105.66
τ 1777
g 0 0
Strong Interaction
γ 0 0
Electro-magnetism
Z0 0 91,188
W± ±1 81,385
Weak Interaction
New
H 0 125,090
2015

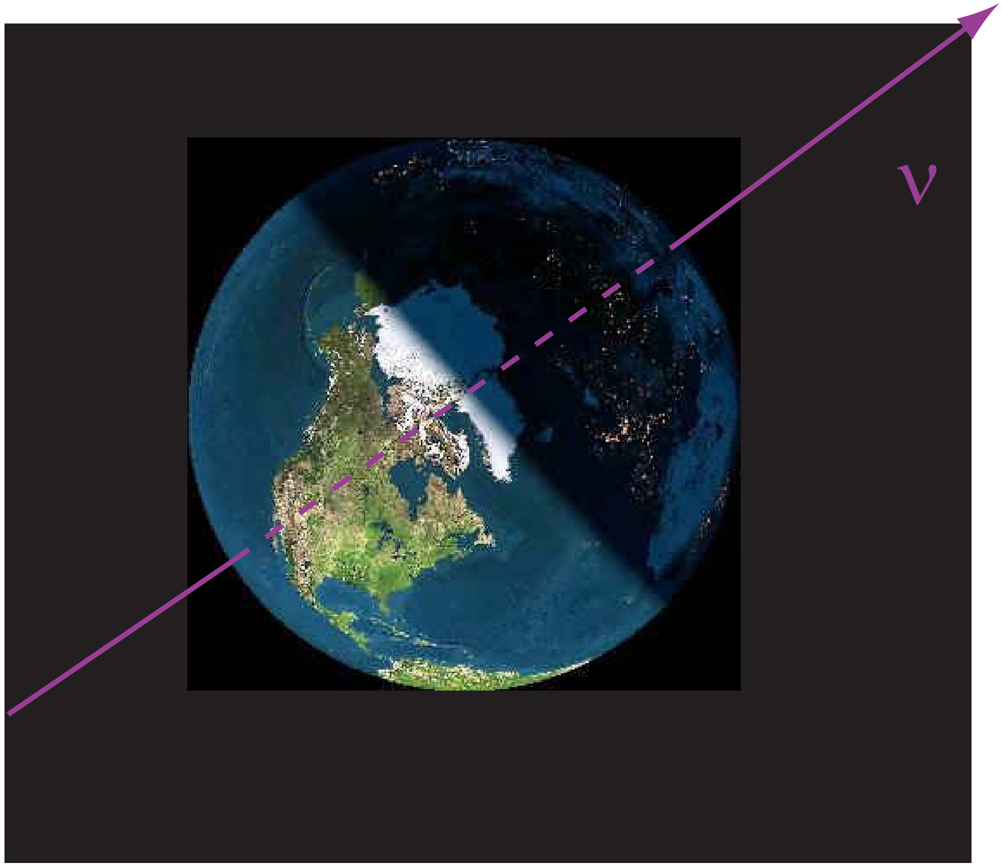
ν neutrinos

Q = -*0*

m = 0?

stable

couples to *W*, *Z*



neutrinos are all over

Neutrinos are created all the time in nature

- The Big Bang left 337 neutrinos/cc.
- The Sun produces 10^{11} neutrinos/second/cm^2
- Cosmic rays in the atmosphere produce around 1 neutrino/cm^2/sec with energy above 100 MeV
- Supernovae can produce up to 10^{58} neutrinos which have a big effect on the explosion.
- Natural radioactive decay produces neutrinos inside you all the time.

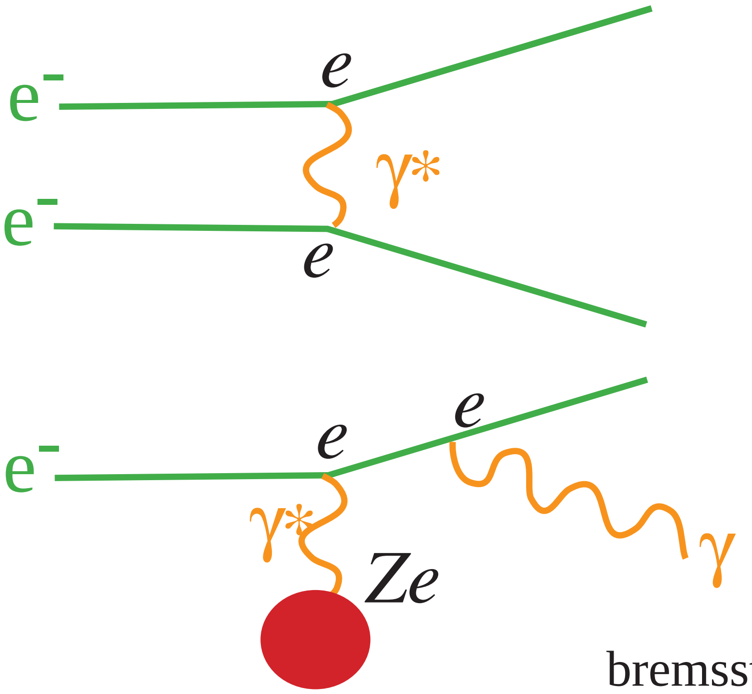
3 known flavors of neutrino

- Neutrinos were first predicted by Pauli in 1930. Radioactive decays like $n \to p + e^- + \overline{\nu}_e$ lacked energy and momentum balance.
- The electron neutrino - discovered by Cowan, Reines et al. using reactor neutrinos in 1956.
- The muon neutrino - discovered by Lederman, Schwartz and Steinberger et al. in 1962 at Brookhaven using an artificial neutrino beam.
- The tau neutrino - discovered in the DONUT experiment at Fermilab in 2000.

These are the flavor or interaction eigenstates of the neutrinos. Telling neutrinos apart is largely a problem of detecting $e^\pm$, $\mu^\pm$, $\tau^\pm$ in the final state.

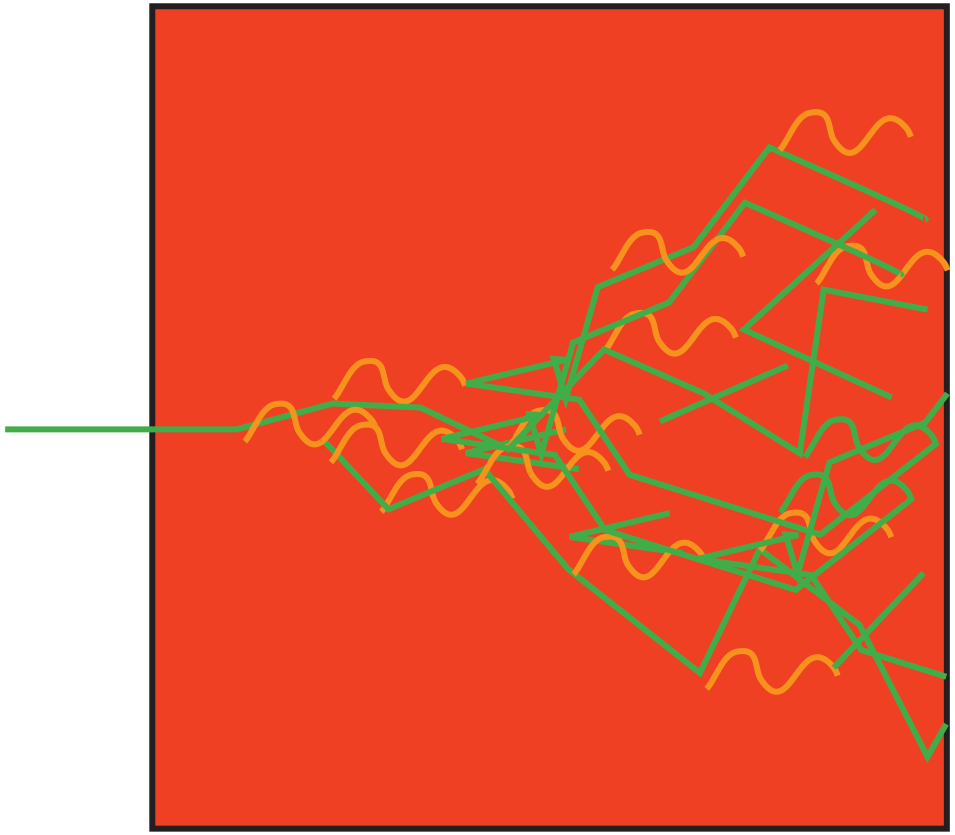
e electron

Q = -*e*
m = 0.511 MeV/c^2
stable
couples to γ, W, Z



bremsstrahlung

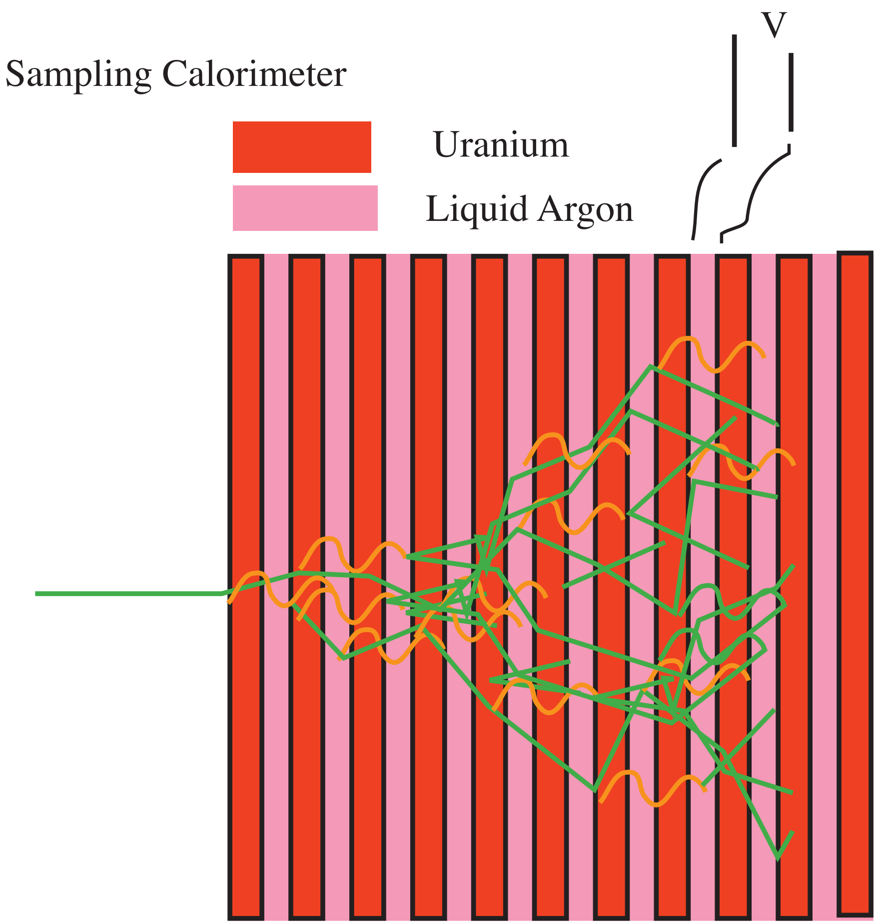
Electron detection



electron bremsstrahlungs,
photon pair-produces, electrons radiate, products do the same. Length scale for one interaction is

X0 ~ 0.3 cm in lead, 9 cm in silicon

Shower length ~ X0 log(ZE)

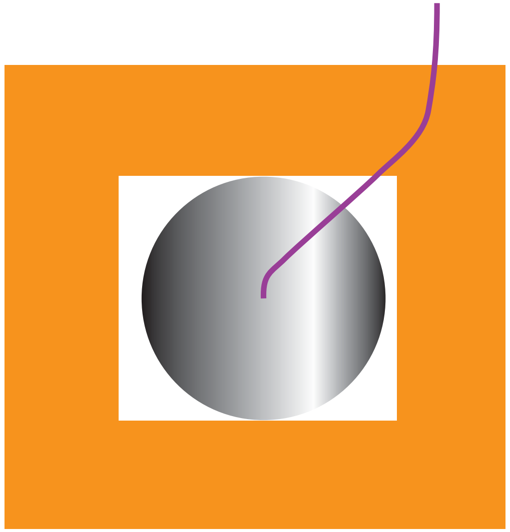


Electrons knocked loose in the Argon are detected
5- 10%/sqrt(E) energy resolution

μ muon

$Q = -e$
$m = 105.66\ \mathrm{MeV}/c^2$
decays to $e\bar{\nu}_e\nu_\mu$
couples to γ, W, Z

Muons are easy to detect because they don't interact much.They don't shower like electrons and they are not sensitive to the strong interaction.

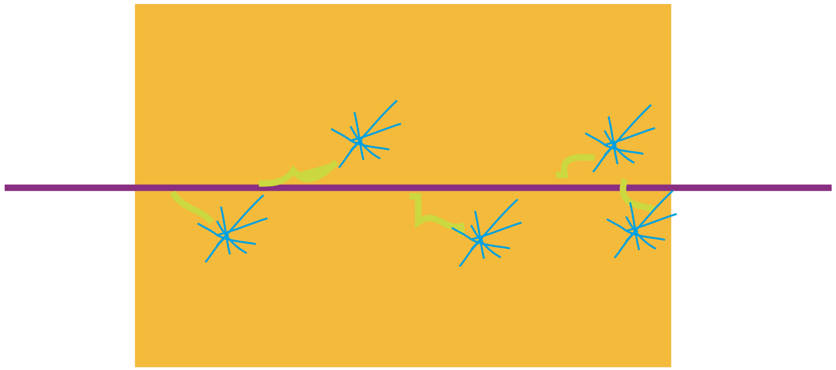


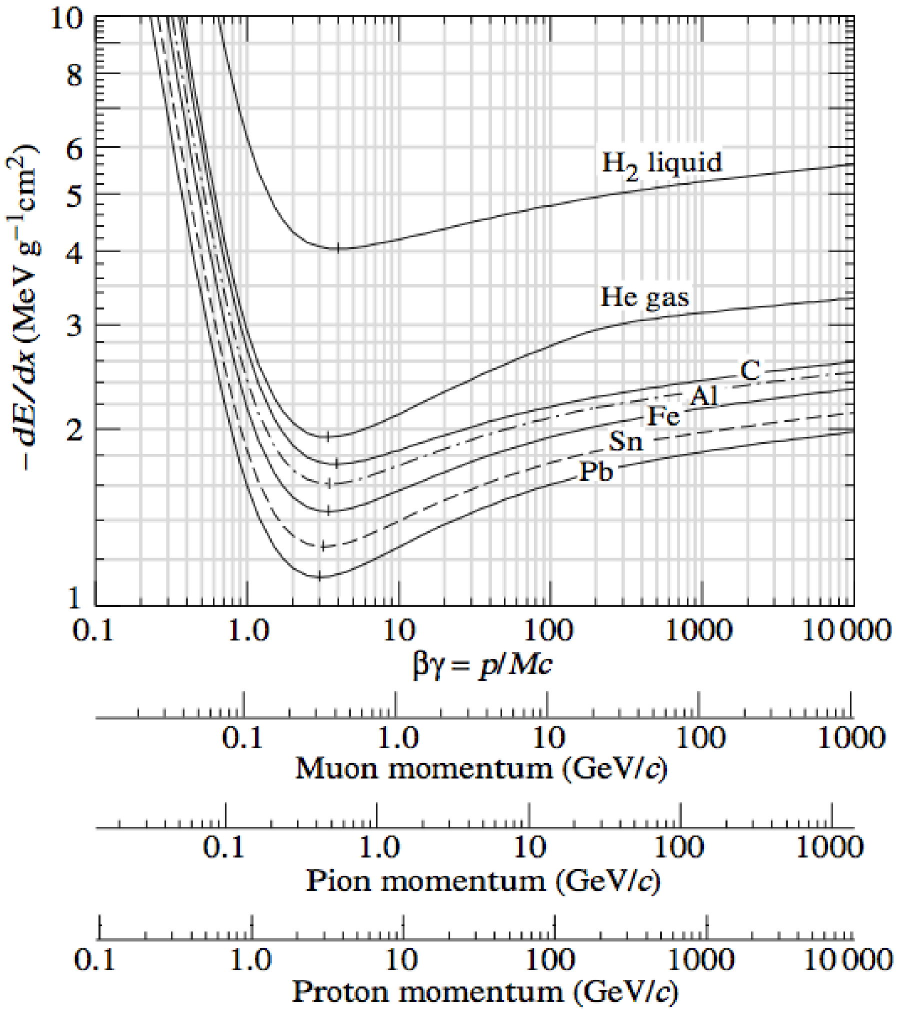
A muon goes thru the D0 calorimeter and toroid magnet.

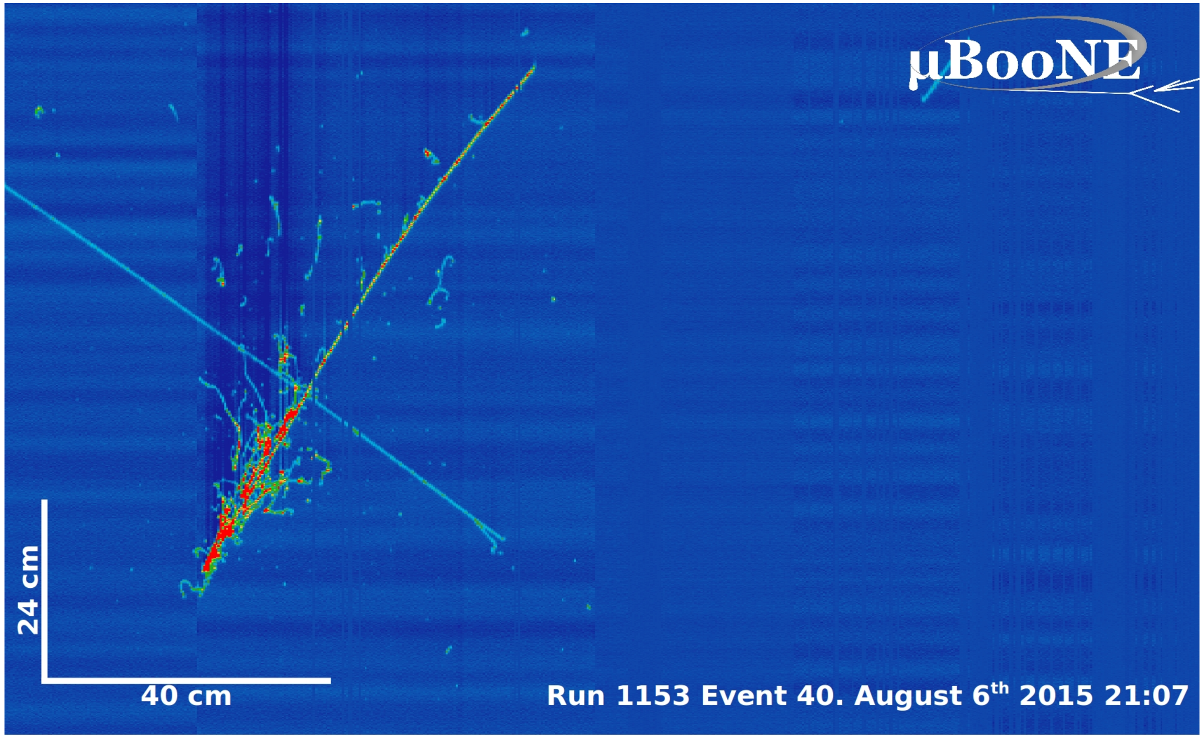
Charged particles with m >> m_e deposit energy at a reasonably constant rate.

$dE/dx \sim Z^2/\beta^2 \rho(g/cm^2)$

Typical energy loss for a fast muon is 2 MeV/gr/cm^2







a muon and a likely electron in the MicroBooNE liquid argon TPC.

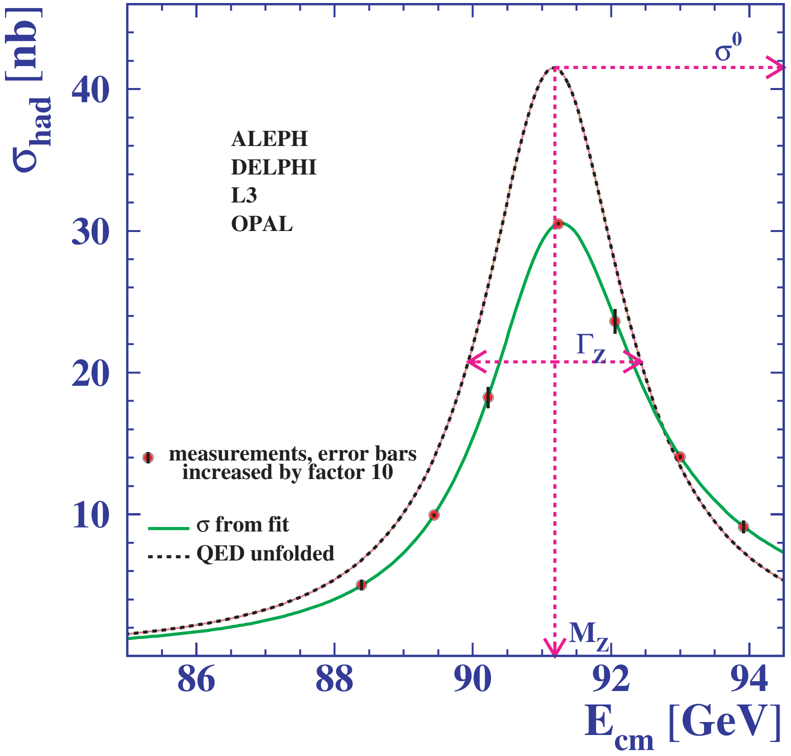
Why do we think we have seen all of the neutrino species?

Z^0's were produced at LEP through the process $e^-e^+ \to Z^0 \to f\overline{f}$ where f are the fundamental fermions. fermion final states there is interference with $e^-e^+ \to \gamma^* \to f\overline{f}$. The total width of the Z^0 is

$$\Gamma_{tot} = \Gamma_{e\overline{e}}+\Gamma_{\mu\overline{\mu}}+\Gamma_{\tau\tau^+}+\sum_{i=1,N_\nu}\Gamma_{\nu\overline{\nu}}+3(\Gamma_{u\overline{u}}+\Gamma_{d\overline{d}}+\Gamma_{s\overline{s}}+\Gamma_{c\overline{c}}+\Gamma_{b\overline{b}})+\text{anything else} \tag{1}$$

The sum is over the number of neutrino species which couple to the Z^0, the various Γ's depend on the couplings to the Z^0 and the factor of 3 for quarks is for the 3 color species. QCD corrections add factors of order α_s to the quark modes due to final stage gluon radiation.

Γ_{tot} can be measured from the width of the Z^0 production rate:



The cross section for hadron production near the Z pole from LEP. The points represent data from the four experiments

The measurement

- The measured width Γ_{tot} is consistent with the known quark and lepton species, with $N_\nu = 2.97 \pm 0.03$ and no other particles with masses less than $m_{\rm Z}$ which couple to the Z^0.
- Our conclusion is that there are only 3 neutrino species with masses less than Z^0 that couple to the Z^0.
- One has to hypothesize a *sterile* neutrino to avoid the LEP bound.

Interaction Basics

Cross sections are the physics observables for scattering.

We we actually measure is the reaction rate between a beam of A's and a target made up of B's which gives a final state X.

$$A + B \to X$$

What determines the rate?

- the physics of the process $A + B \to X$.
- the beam flux F_A which is the number of A hitting the target/cm^2/sec.
- the volume of target hit by the beam $= a \times T$ where a is the area and T is the target thickness
- the number of B per cubic centimeter

$$N_B(cm^{-3}) = \rho_B(gr/cm^3) \times N_{Av}(AMU/gr)/m_B(AMU)$$

Here ρ_B is the density of the material, N_{Av} is Avagadro's number and m_B is the mass of B in atomic mass units.

If you want to compare to other experiments, you need to separate the physics from the experimental setup.

$$Rate(sec^{-1}) = F_A(cm^{-2}sec^{-1}) \times a(cm^2) \times T(cm) \times N_B(cm^{-3}) \\ \times \sigma(A + B \to X)$$

here σ is a quantity which does not depend on the incoming beam, or the target size, but only on the nature of A and B. It has units of cm^2. This is the cross section.

the quantity

$$\mathcal{L}(cm^{-2}sec^{-1}) = F_A(cm^{-2}sec^{-1}) \times aT(cm^3) \times N_B(cm^{-3})$$

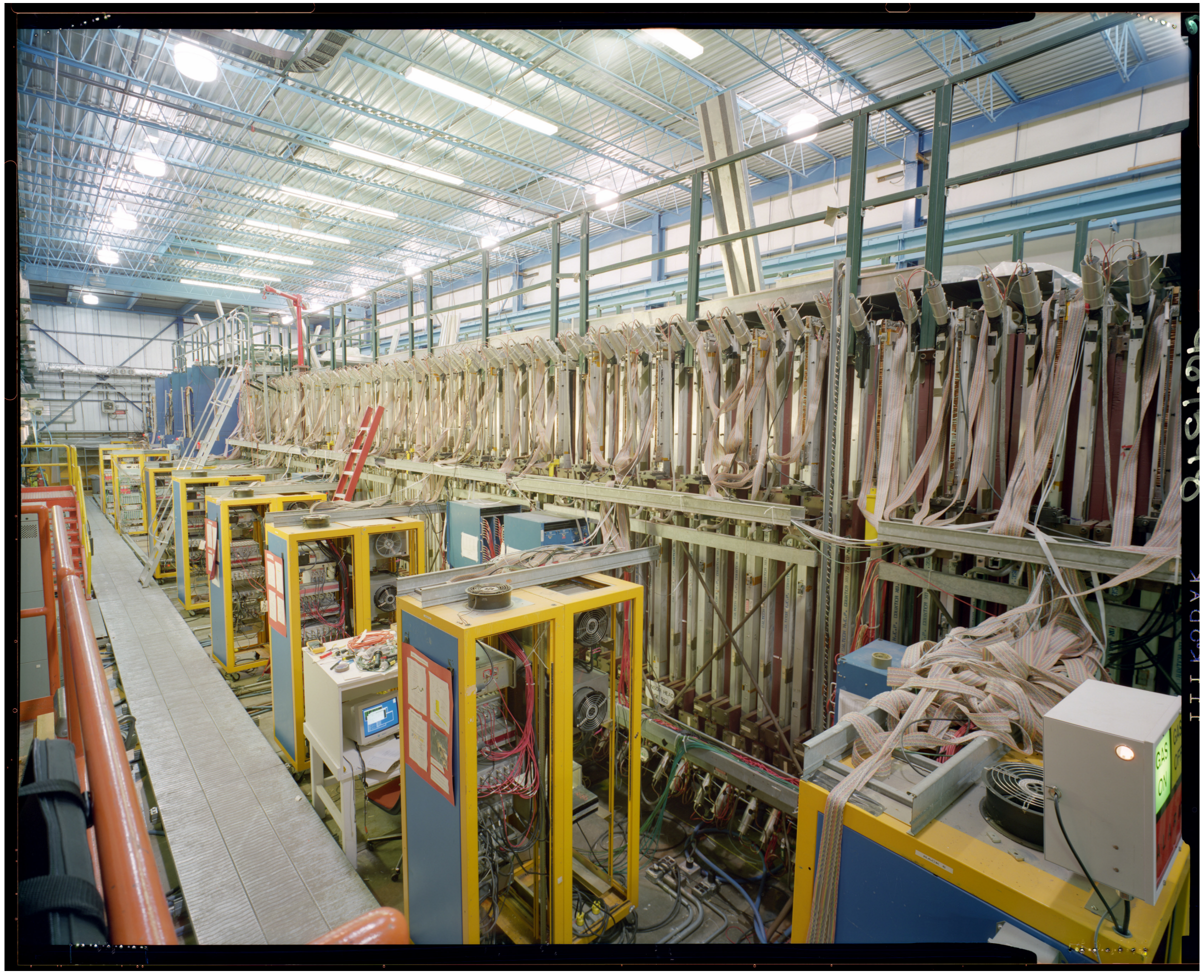
is the "luminosity".

Luminosity sometimes means $\mathcal{L}$ the **instantaneous luminosity** and sometimes $\int \mathcal{L}dt$, the **integrated luminosity**.

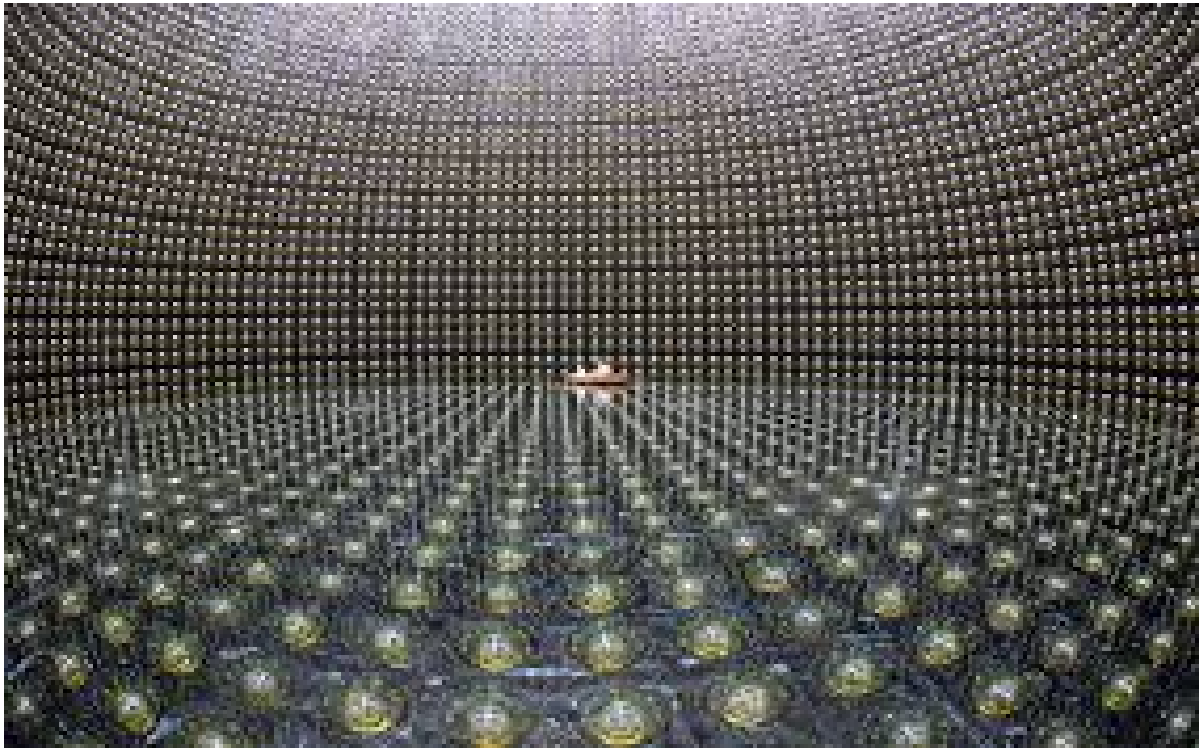
Cross section units are either cm^2 or barns, where a barn is $10^{-24}cm^2$. Typical cross sections at hadron colliders are

- 70 mb $= 7 \times 10^{-26}cm^2$ for the total cross section or
- $\simeq 60$ pb $= 6 \times 10^{-35}cm^2$ for the Higgs boson at 14 TeV.
- Typical neutrino cross sections are in the $10^{-42} - 10^{-38}cm^2$ range!.

At the LHC, an instantaneous Luminosity of 10^{34} cm^{-2}/sec^{-1} has been achieved. Neutrino experiments, which collide neutrinos with tons of material instead milliamps of current can have Luminosities of 10^{37}cm^{-2}/sec^{-1} at the cost of having to instrument tons of stuff.

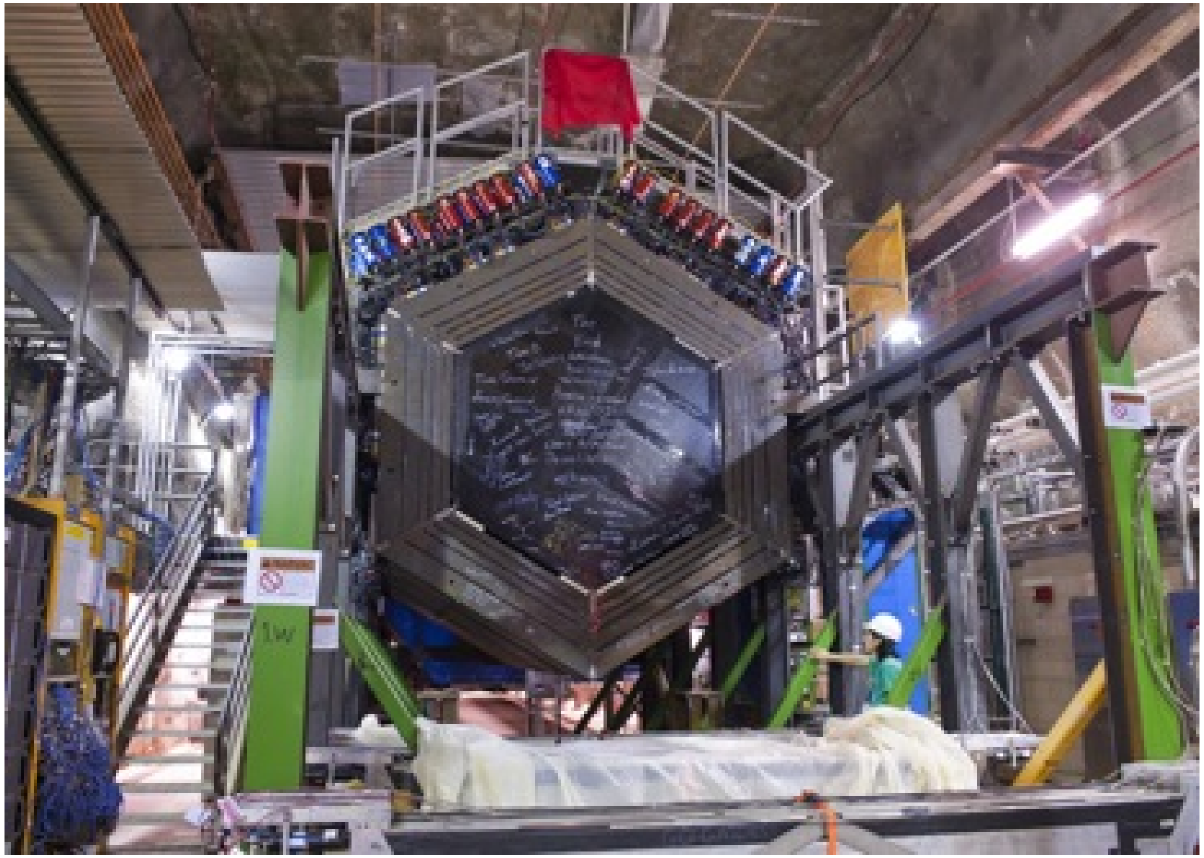


780 Tons of instrumented steel and 5% scintillator at NuTeV



Filling the 50 kTon SuperKamiokande detector with water, read out at the edges.

The 700 Ton ICARUS Liquid Argon TPC being refurbished at CERN

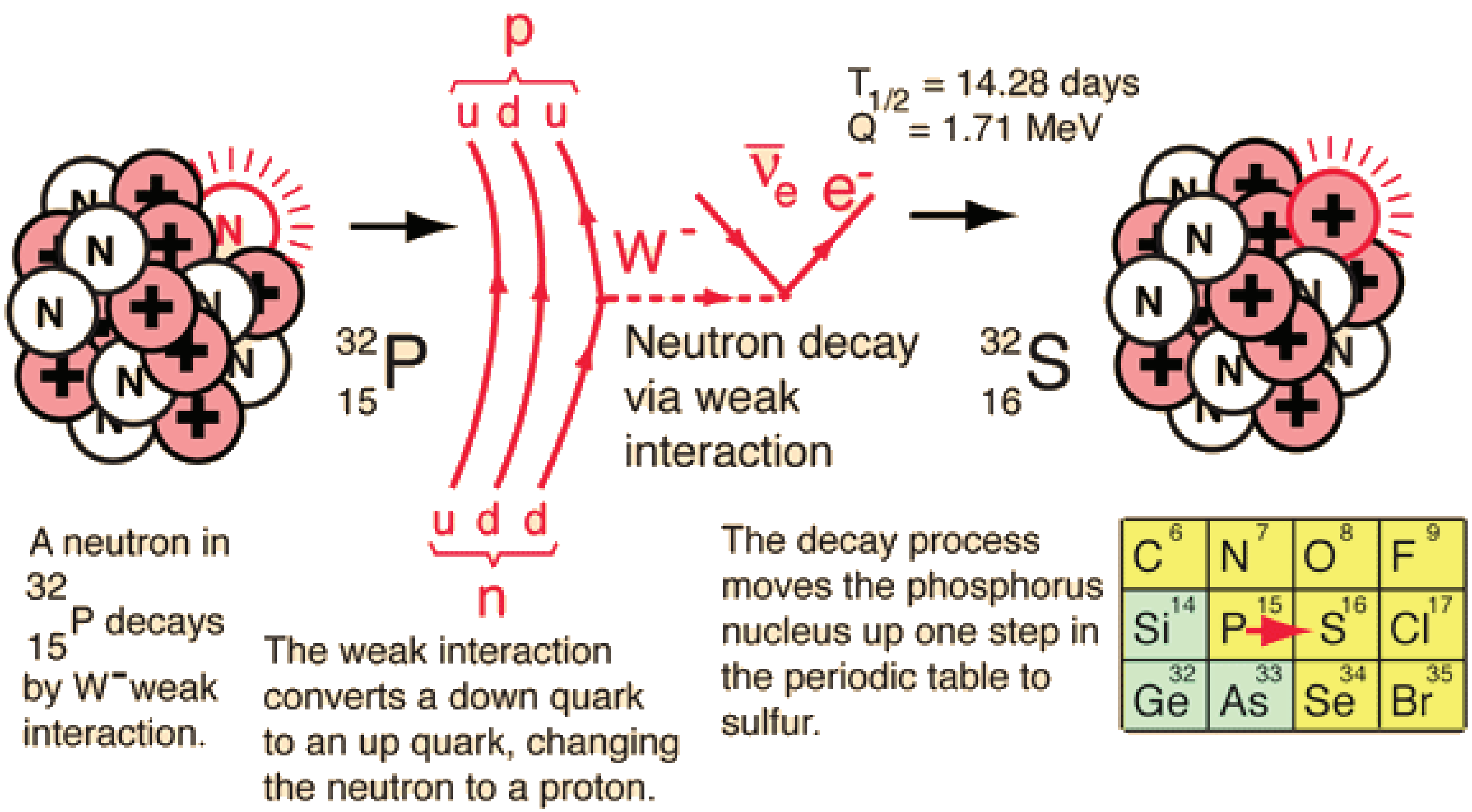


The 5 Ton MINERvA scintillator detector at Fermilab

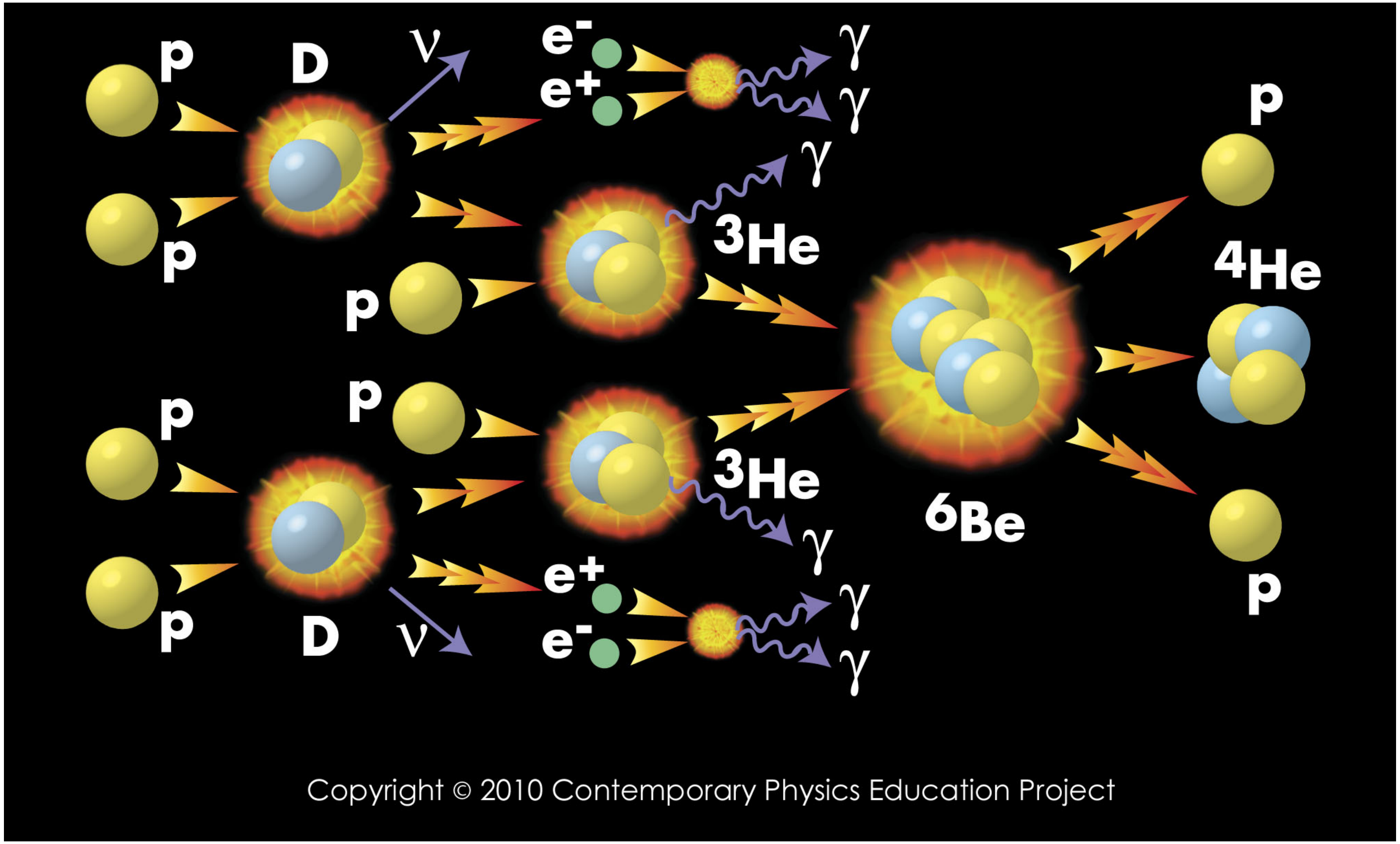
How to make lots of neutrinos

Neutrinos are created in weak interactions. The major sources we have are:

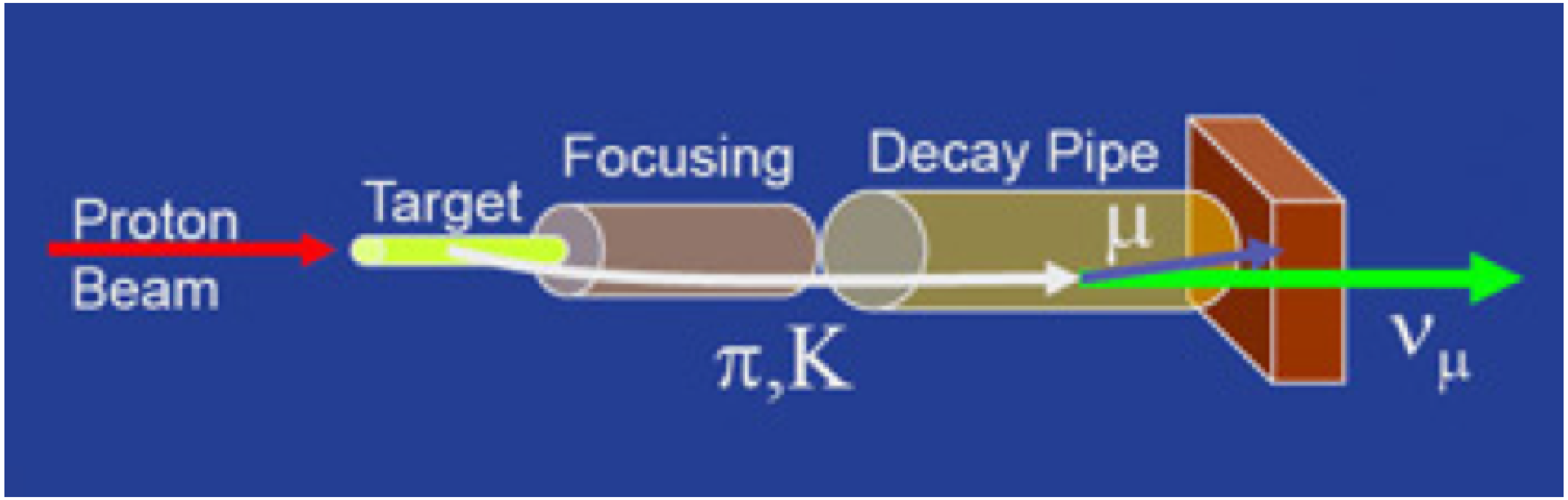
- Nuclear decay - for example reactors.
- Fusion in the sun
- Pion and kaon production - at accelerators and from cosmic rays



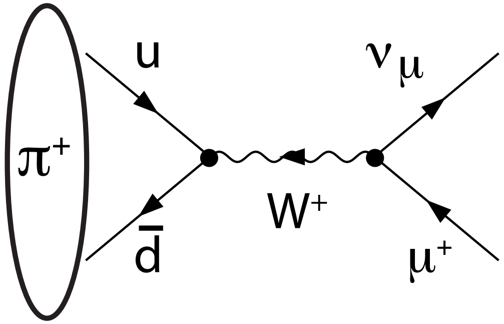
http://hyperphysics.phy-astr.gsu.edu/



Solar neutrinos have energies from $0.1 - 10$ MeV.



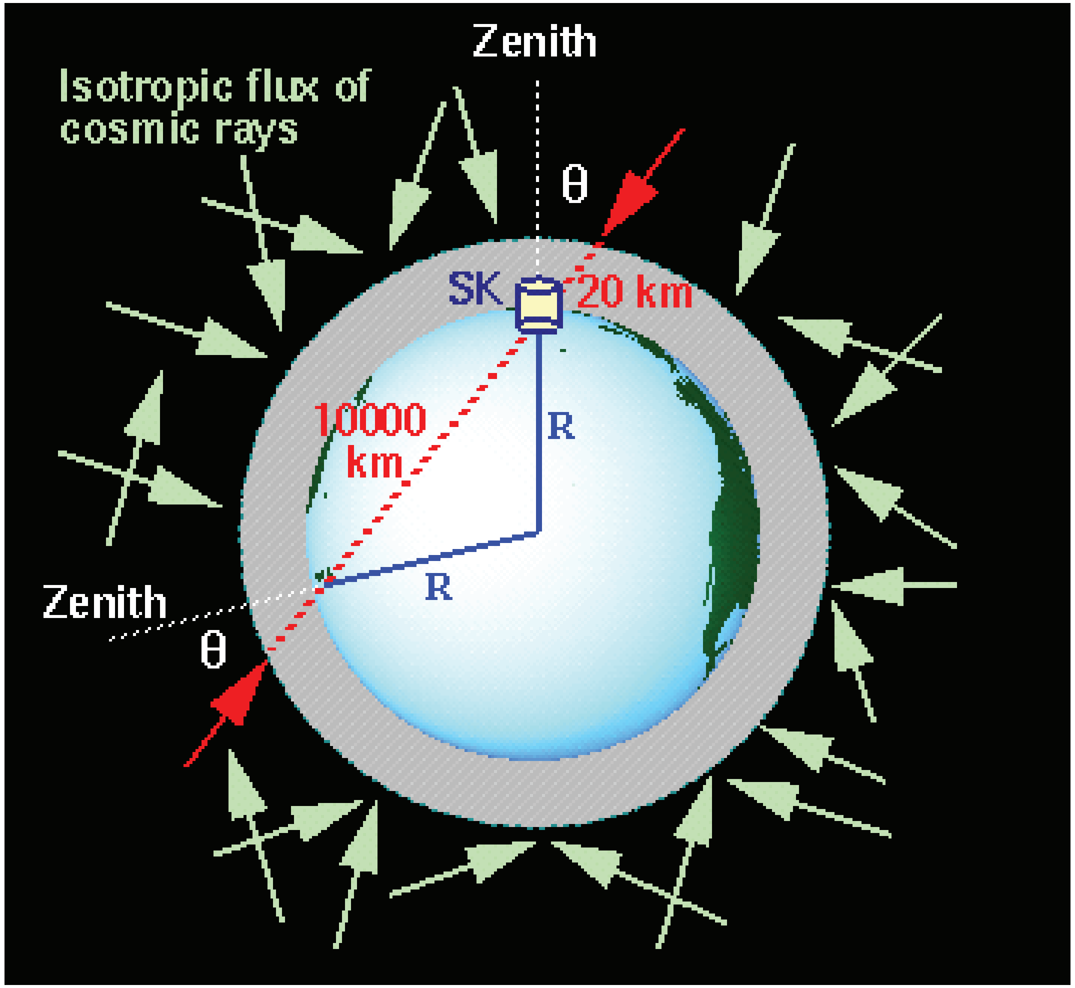
Making a neutrino beam by making pions and letting them decay.

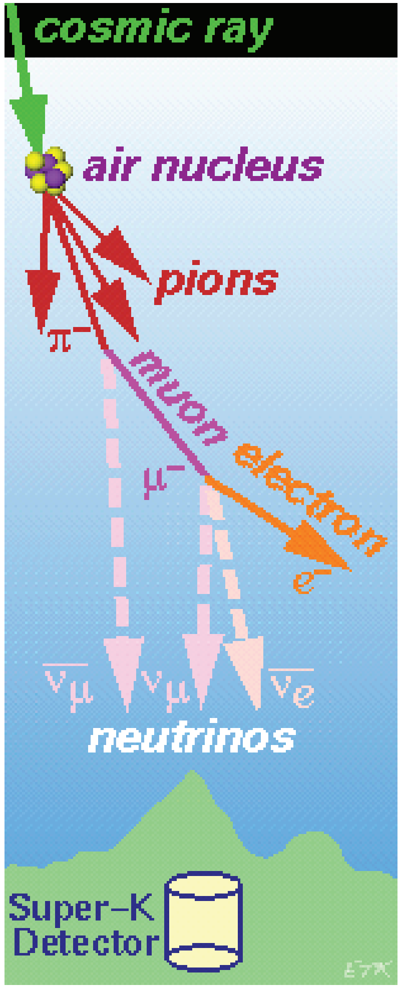


In the CM frame the muon momentum is $p_{cm} \approx 30$ MeV. This means that in the lab, a 3 GeV neutrino could come out at angles of up to

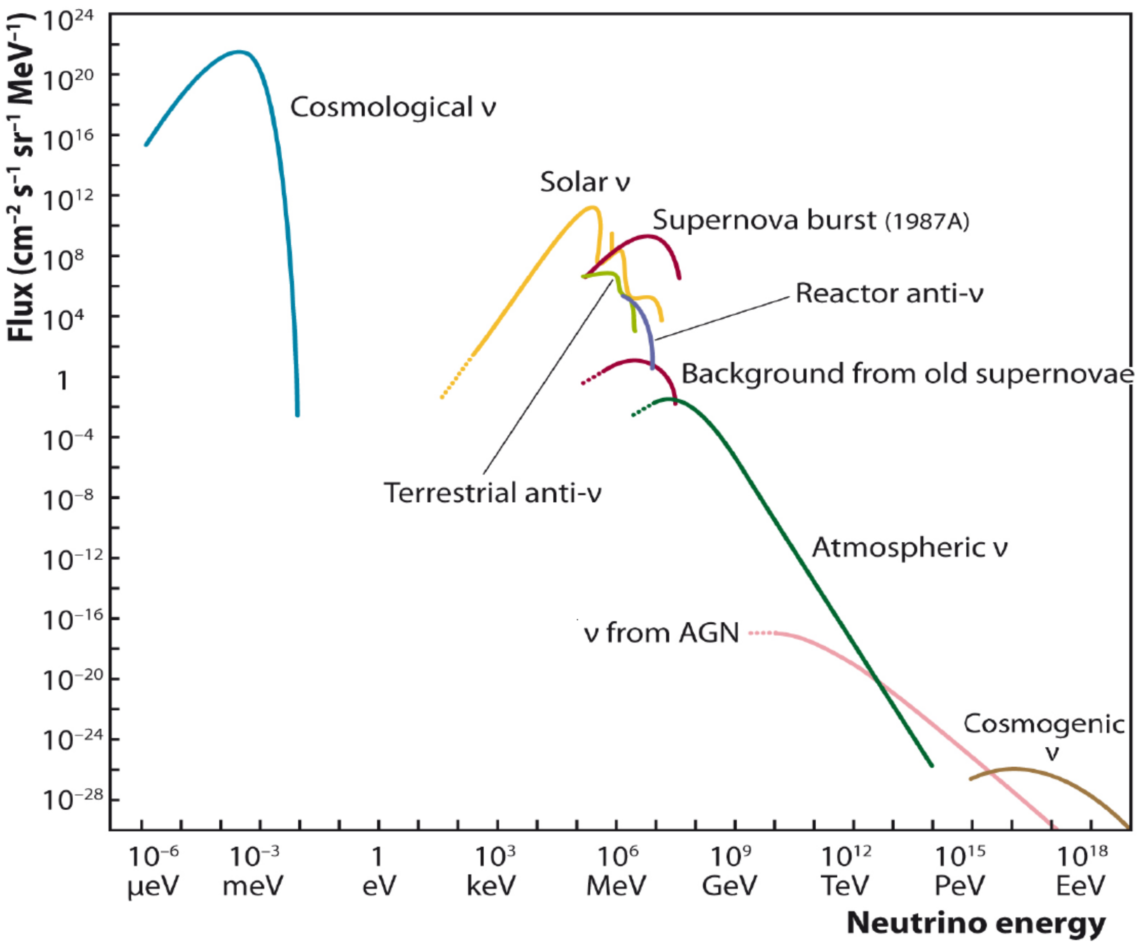
$$\theta \lesssim p_{cm}/p_{lab} \approx 10mr$$

So neutrinos are spread across a wide area no matter how well you focus your pion beam.


Zenith
Isotropic flux of cosmic rays
θ
SK
20 km
10000 km
R
R
Zenith
θ


cosmic ray
air nucleus
pions
π⁻
muon
μ⁻
electron
e⁻
neutrinos
Super-K Detector

From SuperK



Katz, U.F. et al. Prog.Part.Nucl.Phys. 67 (2012)

Experimental cross section

Say I want to measure the cross section for charged current neutrino scattering off of a certain type of nucleus using a muon neutrino beam?

The process will be $\nu_\mu + A \rightarrow \mu^- + X$.

My muon detector doesn't cover all angles, so I lose muons outside the detector. This is called **acceptance**, A. My detector doesn't always work perfectly either so I lose some more muons. This is called **efficiency** ϵ.

And there can also be backgrounds. Very infrequently some other particle like a pion or kaon can fake a muon in my detector. This is **background**, B.

The rate I actually observe is

$$R(\nu_\mu + A \to \mu^- + X) = \sigma(\nu_\mu + A \to \mu^- + X) \times A(\mu^-) \times \epsilon(\mu^-) \times \int \mathcal{L} + B$$

Where $\int \mathcal{L}$ is the time integral of the luminosity and contains information about the running time, beam flux and target thickness.

Fortunately I can normally estimate ϵ using the data and A and B using some theoretical models.

Review of scattering kinematics

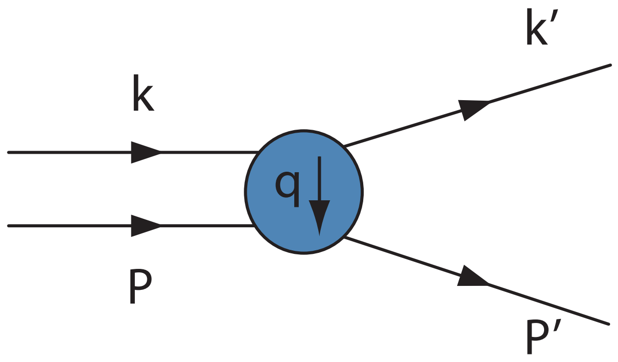
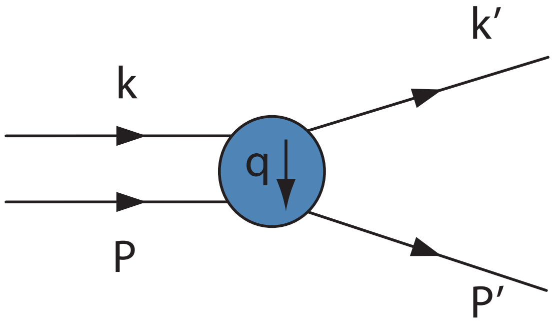


Figure 1: A generic scatter of a lepton off of some target. k^μ and k'^μ are the 4-momenta of the lepton and P^μ and P'^μ indicate the target and the final state of the target, which may consist of many particles. $q^\mu = k^\mu - k'^\mu$ is the 4-momentum transfer to the target.

Lorentz invariants



The 5 invariant masses $k^2 = m_\ell^2$, $k'^2 = m_{\ell'}^2$, $P^2 = M^2$, $P'^2 \equiv W^2$, $q^2 \equiv -Q^2$ are invariants. In addition you can define 3 Mandelstam variables:
$s = (k+P)^2$, $t = (k-k')^2$ and $u = (P-k')^2$.
$s+t+u = m_\ell^2 + M^2 + m_{\ell'}^2 + W^2$. There are also handy variables
$\nu = (p \cdot q)/M$, $x = Q^2/2M\nu$ and $y = (p \cdot q)/(p \cdot k)$.

General form for the cross section in terms of the matrix element

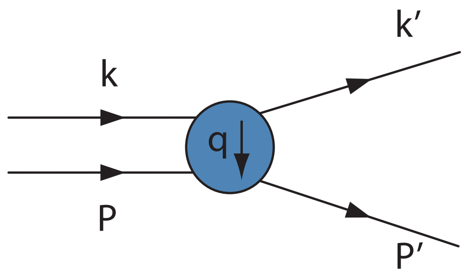
$$\sigma = \frac{(2\pi)^4}{\sqrt{(P_{\mu A}P_B^\mu)^2 - (m_A m_B c^2)^2}} \int |\mathcal{M}|^2 \mathcal{S}$$

$$\left[\delta^4(P_A^\mu + P_B^\mu - p_1^\mu ....p_N^\mu) \prod_i \delta(p_i^\mu p_{i\mu} - m_i^2 c^4) \frac{d^4 p_i}{(2\pi)^3}\right]$$

Where P_A and P_B are the 4-momenta of the incoming particles and m_A and m_B are their masses. The term at the end in brackets is the Phase Space. $\mathcal{S}$ is a spin factor to account for summing over final states and averaging over initial states.

A measurement of the cross section is thus a measurement of the matrix element and can be used to test theoretical models and determine matrix element parameters.

2 body scattering

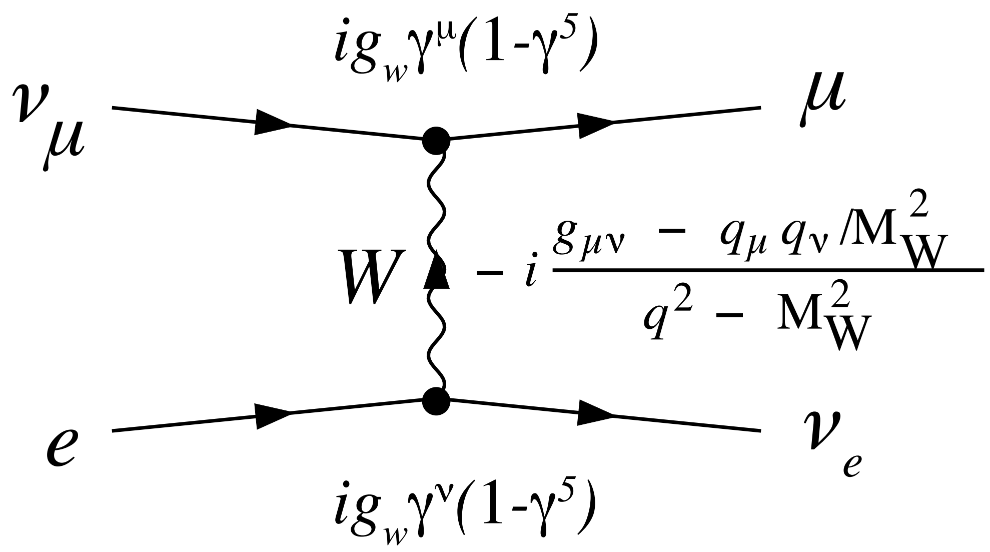


For a 2 body scatter the phase space integral is pretty simple as one particle will recoil against the other and one ends up with something that looks like

$$\sigma = \frac{\hbar^2 c^2}{16\pi} \frac{1}{s} |\mathcal{M}|^2 \times \text{ spin factor}$$

This is as far as we can go without knowing the matrix element M, it may well induce some angular dependence.

Simple neutrino scattering

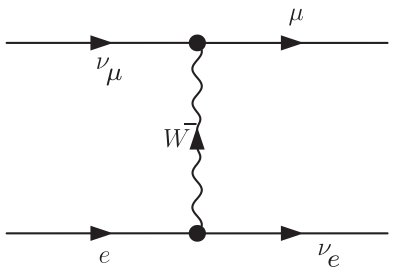


Fermion W vertices get a factor of $i\frac{g_w}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)$. The $(1-\gamma^5)$ factors essentially select out the left-handed polarizations for particles and the right handed polarization for anti-particles. The W completely ignores right-handed particles and left-handed antiparticles. If there were a right-handed neutrino it would not show up in W interactions.

The W boson is massive so it can have 3 polarizations (corresponding to $m = -1, 0, 1$) instead of 2 for the photon and the propagator becomes

$$-i\frac{g_{\mu\nu} - q_\mu q_\nu / M_W^2}{q^2 - M_W^2}$$

Note that the propagator has to wander away from the W mass, not zero for an interaction to occur. If $q << M_W$ weak interactions are very unlikely. As we will see $g_w > g_e$! The reason that weak interactions are weak is the difficulty in getting the W boson to do any work for you.



Given these Feynman rules we can calculate (after some pain) the matrix element

$$\mathcal{M} \simeq \frac{g_W^2}{(M_W^2 - q^2)} \times s \times \left[1 - (\frac{m_\mu^2}{s})^2\right]$$

$$\sigma = \frac{\hbar^2 c^2}{16\pi}\frac{1}{s}|\mathcal{M}|^2 \times \text{ spin factor} = \frac{\hbar^2 c^2}{8\pi} g_W^4 \frac{E_{CM}^2}{(M_W^2 + Q^2)^2} \times [1 - (\frac{m_\mu^2}{s})^2]^2$$

(the neutrino is only left-handed so there is a factor of 2 not 4 for the spin averages.)

This is in the cm frame, in the lab frame $s = 4E_{cm}^2 \approx 2m_e E_{lab}$ so $E_{lab} = 2E_{cm}^2/m_e$.

At high energy

$$\sigma \simeq \frac{\hbar^2 c^2}{16\pi} g_W^4 \frac{E_{lab} m_e}{(M_W^2 + Q^2)^2}$$

The cross section scales with E as long as $Q << M_W$.

Now let's plug in some numbers

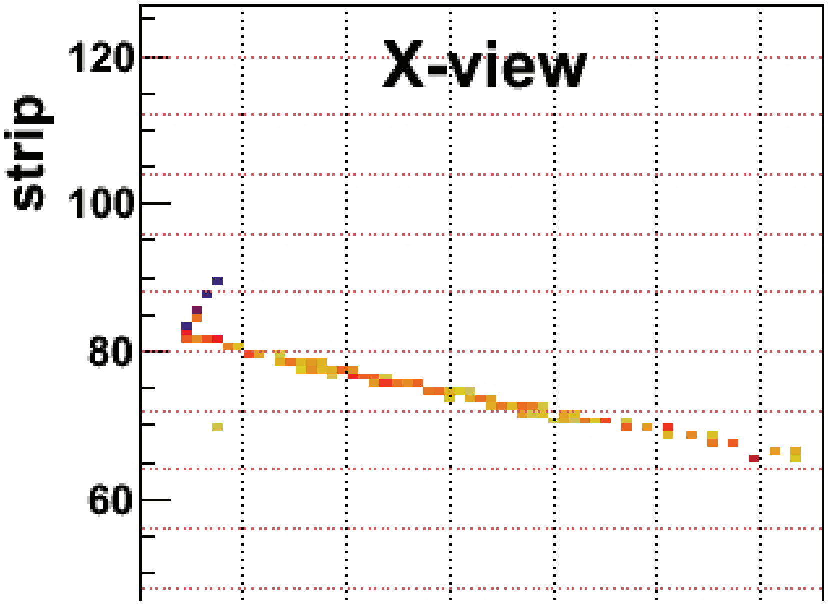
$\hbar c = 0.197$ GeV-fm, $M_W = 80.4$GeV, $g_W = .6295$, $m_e = 0.000511$ GeV and let's take E to be about 100 GeV, which makes $E_{cm} \simeq 0.320$ GeV.

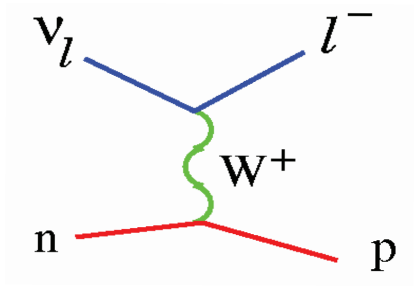
$\sigma = 1.5 \times 10^{-13} fm^2$ or $1.5 \times 10^{-39} cm^2$.

This process has been observed but only about 3000 interactions have ever been seen. It can't happen in anti-neutrinos because an anti-neutrino needs to interact via a W^- or Z^0 and can't conserve charge while producing a $\mu^\pm$.

Quasi-elastic scattering from nuclei

Next most complicated are processes like $\nu_\mu + n \to \mu^- + p$ where the neutrino scatters off a nucleon without breaking it. This is most common at lower energies.

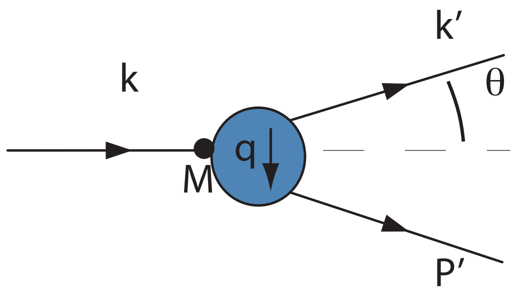




A quasi-elastic neutrino reaction in the Minerva neutrino detector

In the lab frame

Let's scatter an anti-neutrino off of a proton $\overline{\nu}_\mu + p \to \mu^+ + n$



$$
\begin{aligned}
k^\mu &= (E_k, 0, 0, k) \\
P^\mu &= (M, 0, 0, 0) \\
k'^\mu &= (E'_k, k'\sin\theta, 0, k'\cos\theta) \\
q^\mu &= k^\mu - k'^\mu
\end{aligned}
$$

Solving for E_ν

In experiments we often can only measure the outgoing muon k'^{μ}. But if we assume we know the direction of the incoming neutrino and that the proton was at rest we can actually solve for everything else.

$$E_\nu^{QE} = \frac{m_n^2 - m_p^2 - m_\mu^2 + 2m_p E_\mu}{2(m_p - E_\mu + p_\mu \cos\theta_\mu)} \tag{2}$$

$$Q^2_{QE} = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2 \tag{3}$$

The proton is a complex object with finite extent and quarks inside it. As a result, it doesn't have pointlike couplings and has a form (Llewellyn-Smith version):

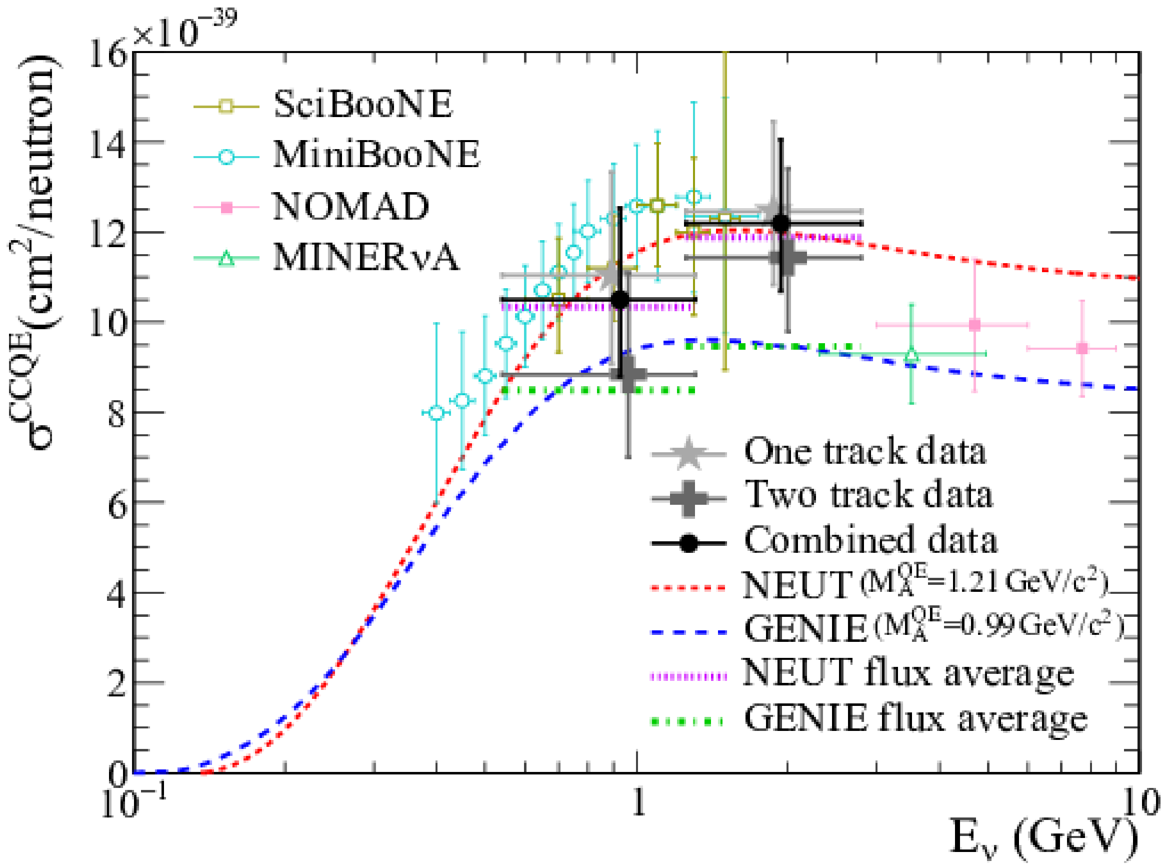
$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}\begin{pmatrix}\nu_l n \to l^- p\\ \bar{\nu}_l p \to l^+ n\end{pmatrix} = \frac{M^2 G_F^2 \cos^2\theta_C}{8\pi E_\nu^2}\left\{A(Q^2) \mp B(Q^2)\frac{s-u}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right\} \tag{4}$$

Where the Fermi Constant

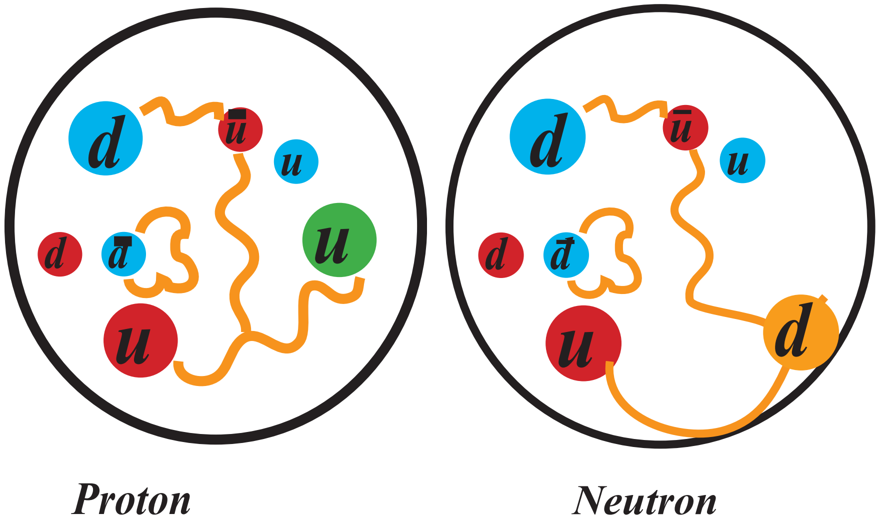
$$G_F \approx \frac{g_w^2}{4\sqrt{2}M_W^2}$$

and the $A, B, C(Q^2)$ contain Form Factors with dependencies like $1/(Q^2 + m_X^2)$ where m_X is an appropriate energy scale. Some of these Form Factors are known from electron-proton scattering but the axial form factor which is sensitive to the weak couplings is less well known.

Quasielastic scattering is very important at low energies but doesn't rise with energy as predicted by the simple point particle calculation.



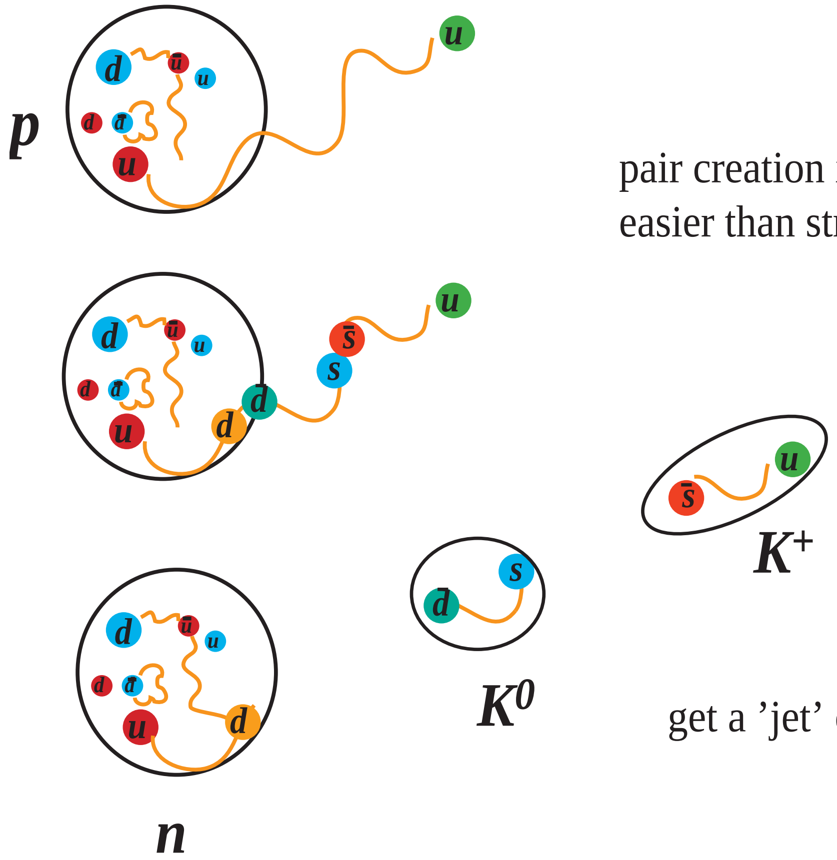
What happens is that as the energy gets to be higher, with $Q \geq m_p$, the neutrino starts to resolve the components in the proton, scatters from only one of the components, and the proton breaks up.



Quark Confinement

Strong force is very strong

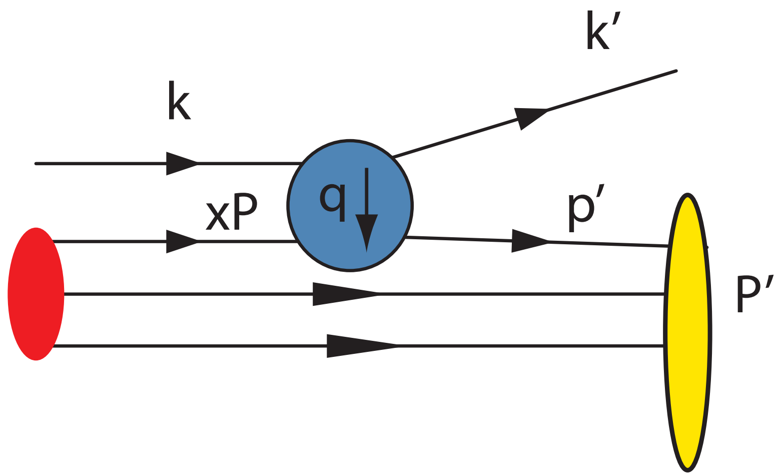
Try to rip one quark out of a proton



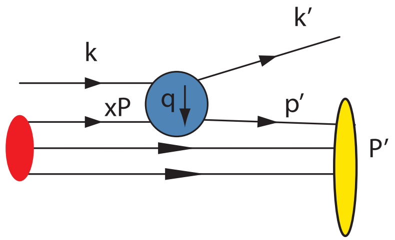
pair creation is
easier than stretching

get a 'jet' of particles

Inelastic scattering



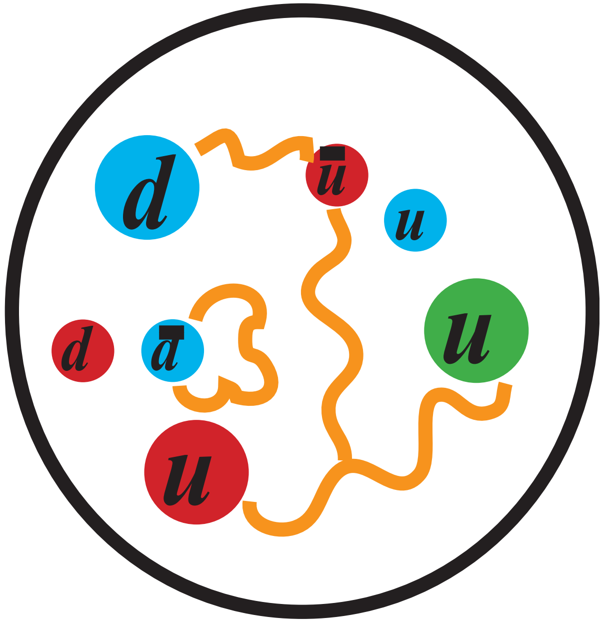
Imagine a quark carrying momentum fraction x of the proton momentum P_P^μ and scatter an muon neutrino off of it. Here we can reconstruct the neutrino energy from the final state energy of the muon and the proton remnant. And we can also reconstruct x if we assume the quark is a point particle. This is one way we know the quark content of the proton.



in a frame where $E_P >> M_P$

$$
\begin{aligned}
k^\mu &= (E, 0, 0, E), \qquad k'^\mu = (E', E'\sin\theta, 0, E'\cos\theta) \\
P_P^\mu &= (E_P, 0, 0, E_P) \\
p^\mu &= xP = (xE_P, 0, 0, -xE_P) \\
p'^\mu &= k^\mu + p^\mu - k'^\mu = q^\mu + p^\mu \\
p^\mu p_\mu &= p'^\mu p'_\mu = x^2 M_P^2
\end{aligned}
$$

The last expression assume the quark is still the same after the scatter.



Proton

Let's try a model of the proton containing just the 3 "valence" u and d quarks.

A proton has 2 u quarks and a d quark.

Naively we'd expect each to carry $1/3$ of the momentum, so the x probability densities would be $\delta(x - 1/3)$.

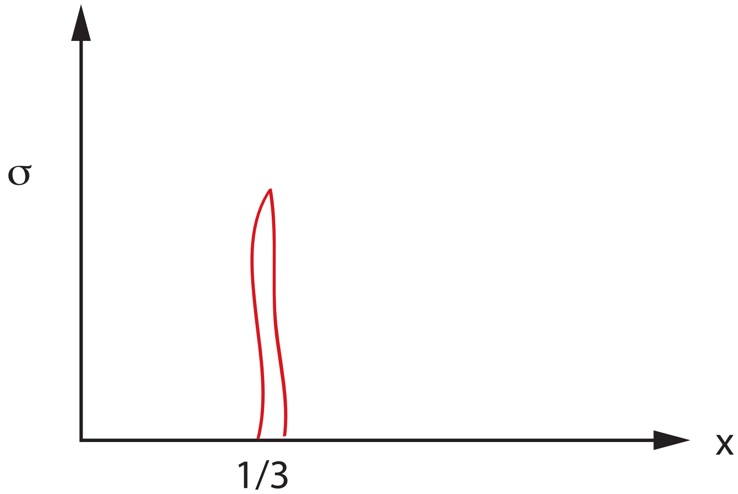
And we could see the process

$$\nu_\mu + d \to \mu^- + u$$

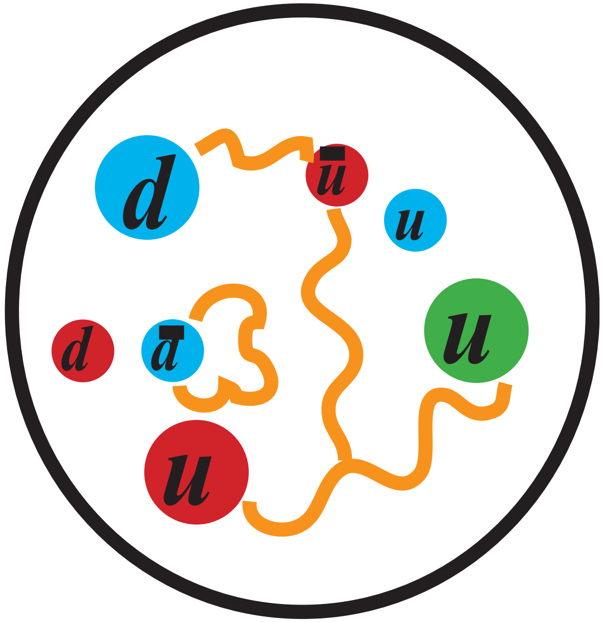
$$\overline{\nu}_\mu + u \to \mu^+ + d$$

But not the opposite as a neutrino has to produce a negative muon in the final state so can only raise the charge of the quark it hits (and vice versa for anti-neutrinos). Neutrinos are great for telling quarks apart!

What we might expect to see



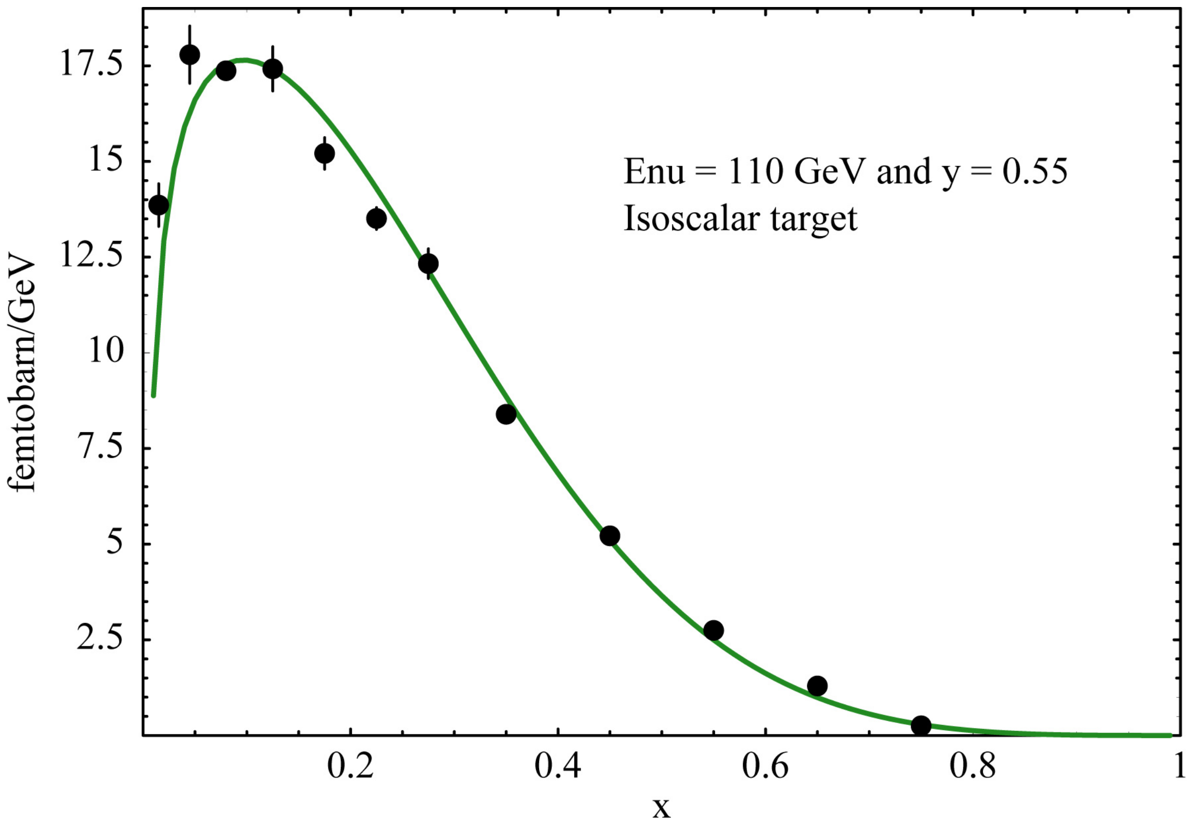
Realistic model of the proton



Proton

Our new model has the proton containing the 3 "valence" u and d quarks but a whole sea of quark anti-quark pairs.

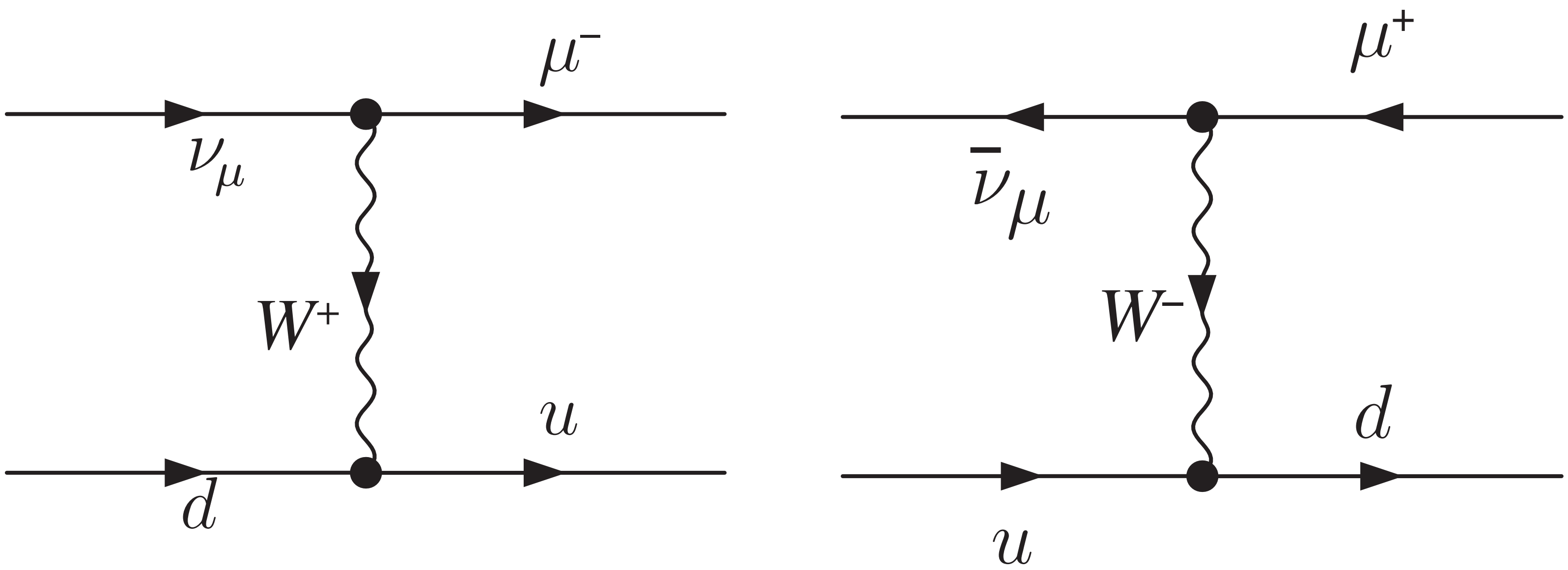
What we actually see



Evidence from neutrino scattering (in this case on Iron) that quarks are spread out in momentum inside the nucleus.

Telling quarks from anti-quarks and u from d

Charge conservation means that some weak interactions can't happen.

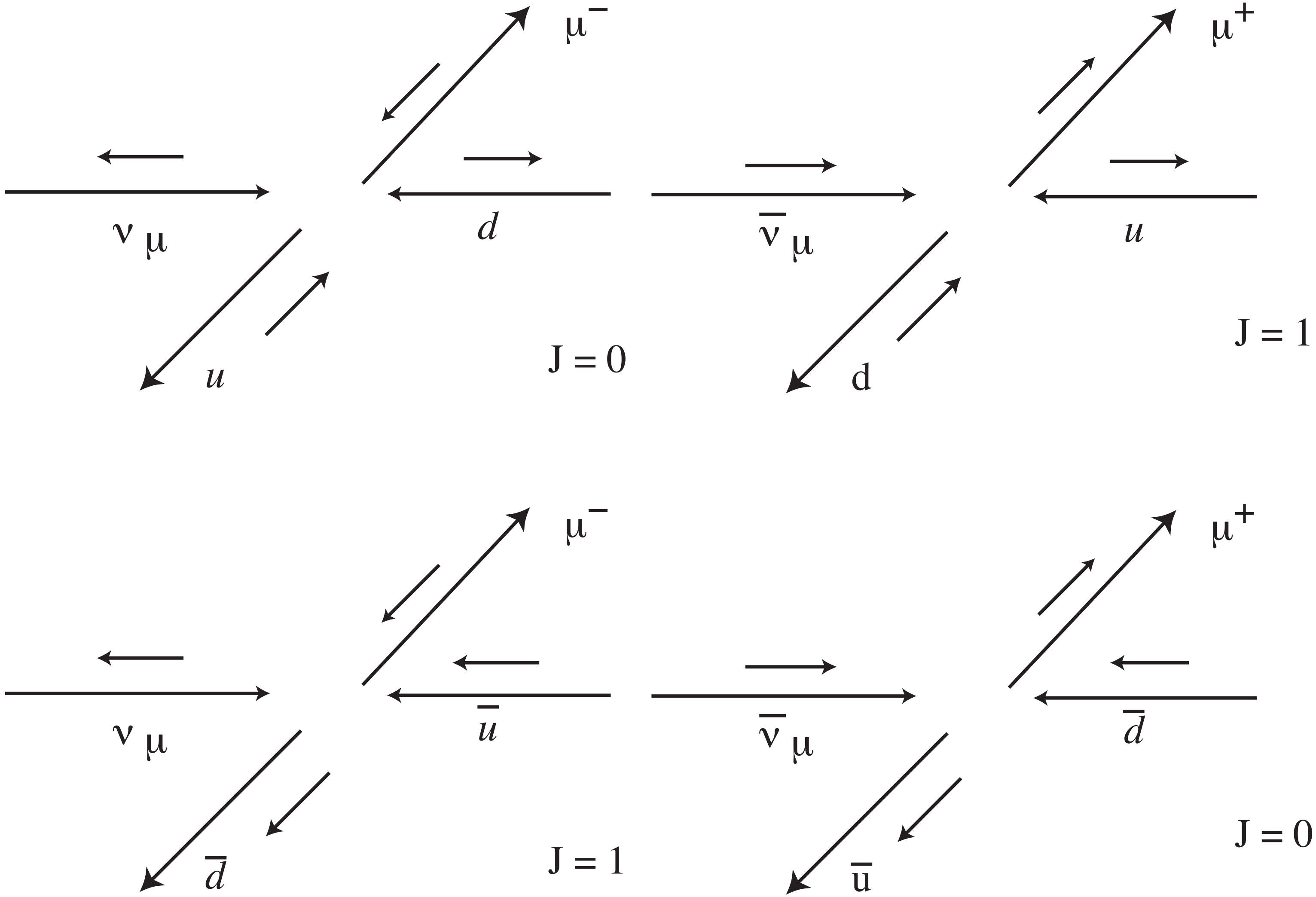


$\nu_\mu \to W^+\mu^-$ and $\overline{\nu}_\mu \to W^-\mu^+$ so

$\nu_\mu d_L \to \mu^- u_L$ and $\nu_\mu \overline{u}_R \to \mu^- \overline{d}_R$,

$\overline{\nu}_\mu u_L \to \mu^+ d_L$ and $\overline{\nu}_\mu \overline{d}_R \to \mu^+ \overline{u}_R$

telling d_L from $\overline{u}_R$



telling d_L from $\overline{u}_R$

The $\nu_\mu d \rightarrow u\mu^-$ scattering cross section was isotropic because a left-handed neutrino interacting with a left-handed d-quark has total spin 0.

For the J=1 processes, like $\nu_\mu \overline{u}_R \rightarrow \mu^- \overline{d}_R$, there is a spin suppression factor of $((1+\cos\theta_{cm})/2)^2 = (1-y)^2$.

We can measure the momentum fraction x carried by these quarks!

At each x the total cross section will be depend on the probability of there being a quark of fraction x around and on the rate for hard electron-quark scattering.

So

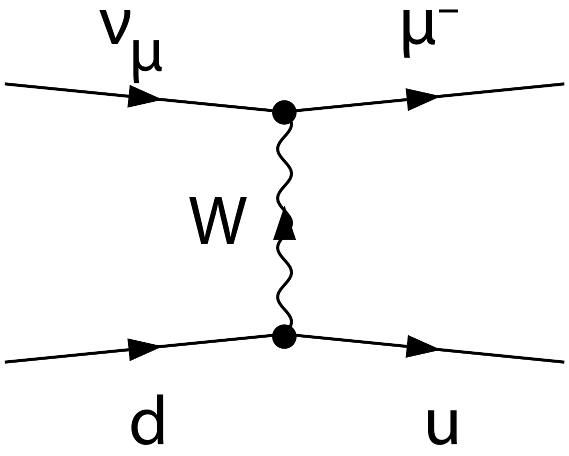
$$\frac{d\sigma}{dx}(\nu_\mu + p \to \mu + X) = \sum_i \frac{d\hat{\sigma}}{dx}(\nu + q_i \to \mu + q_i; \hat{s}, \hat{t}, \hat{u}) f_i(x)$$

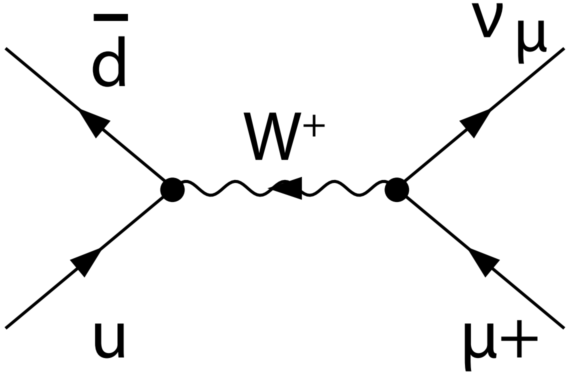
By measuring $\frac{d\sigma}{dx}$ on different targets and using the simple predictions for the $\hat{\sigma}(\nu_\mu + q_i \to \mu + q_i; xs)$ one can measure the different $f_i(x)$.

Historical Note

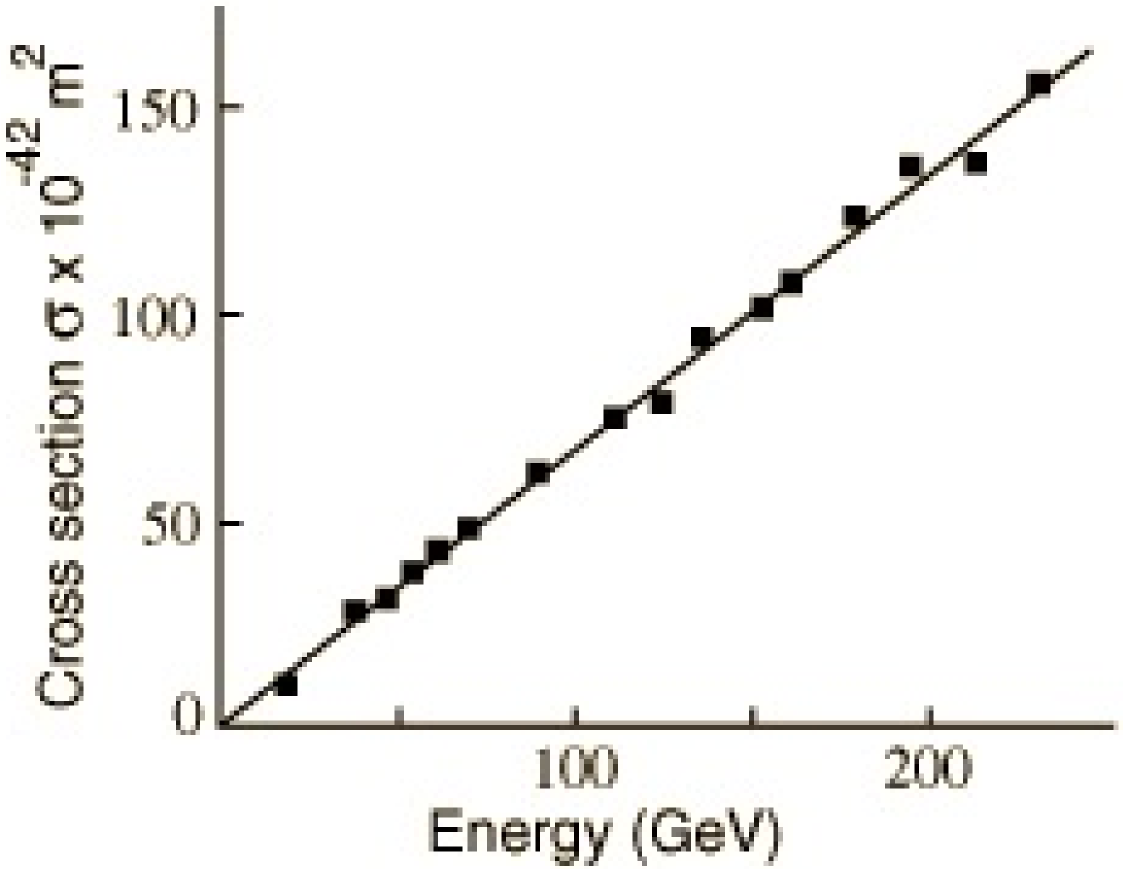
This is how we used to do it.

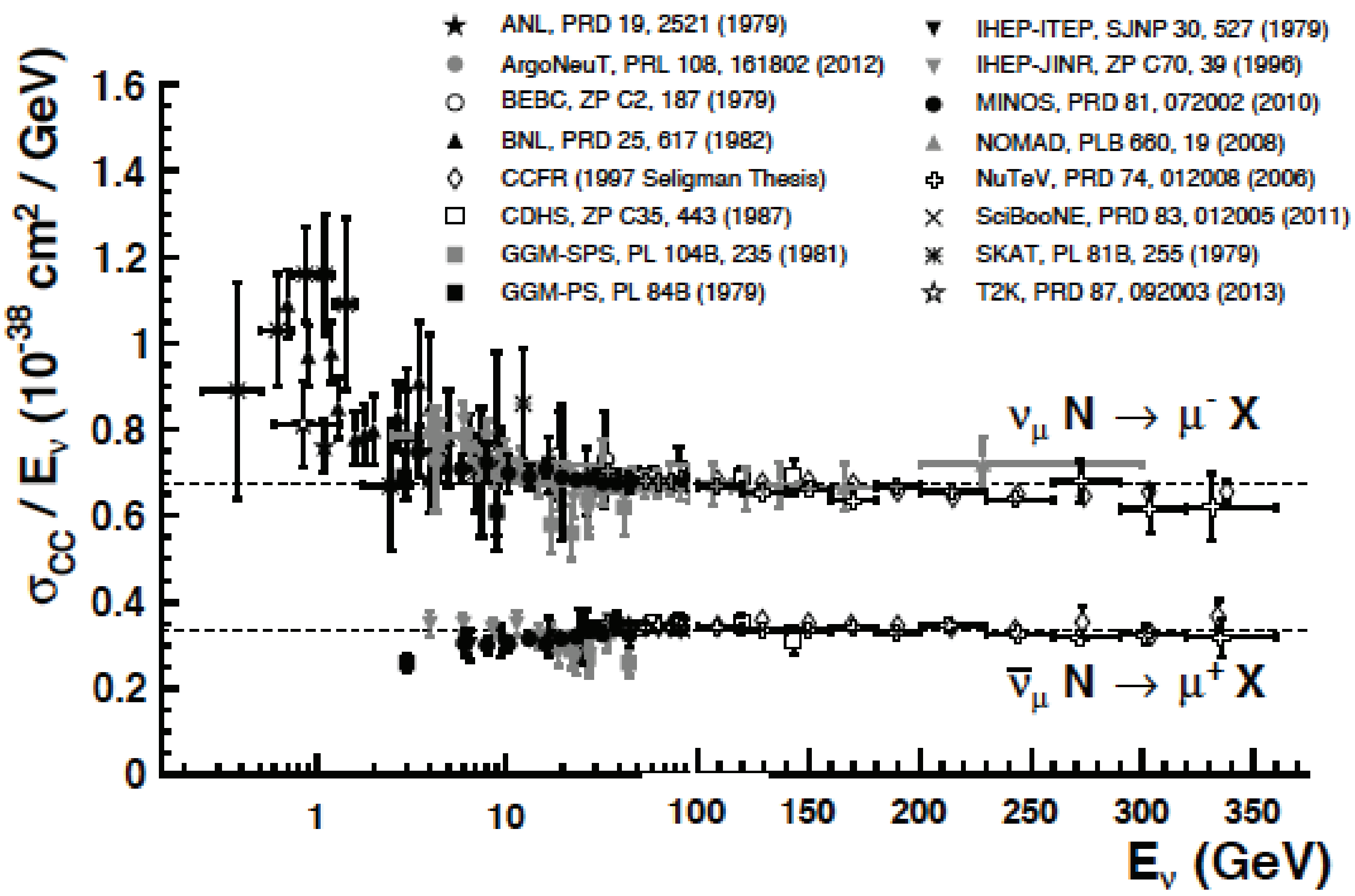
Now experiments like CMS and ATLAS flip the interaction and produce real W bosons to study the quarks in protons.



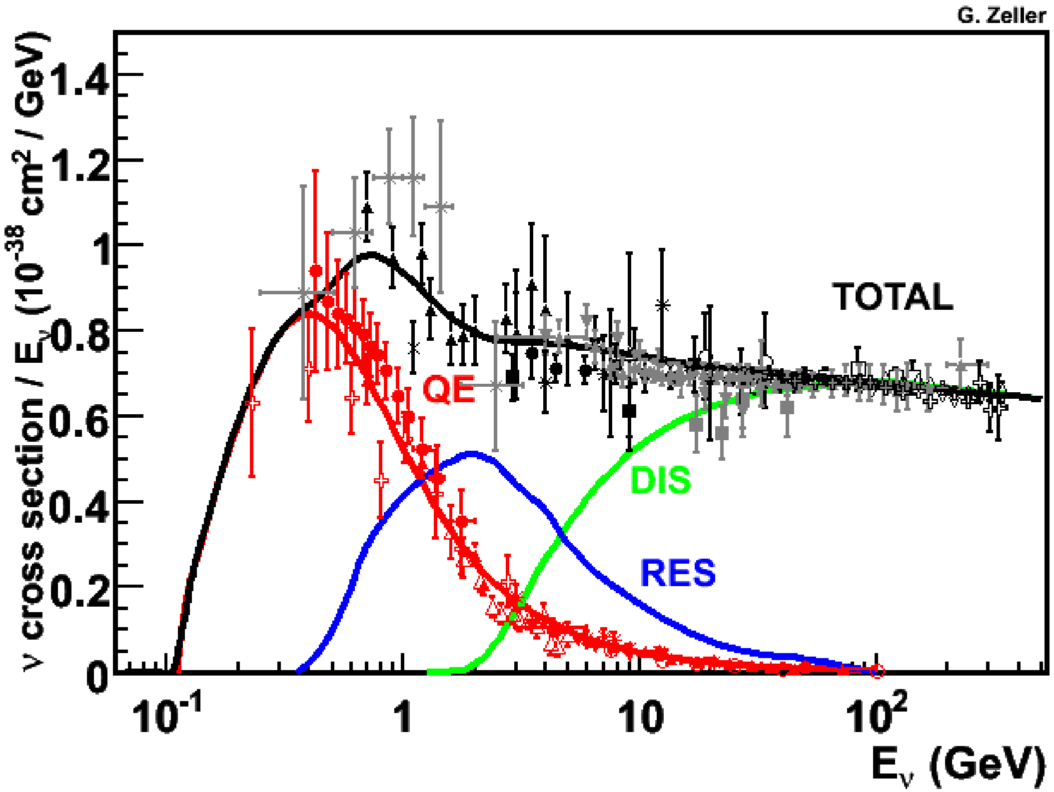


We also expect that the total cross section will look like the sum of a large number of scatters off of point particles and we will recover the linear dependence on E_{lab} we saw for scattering off of an electron.





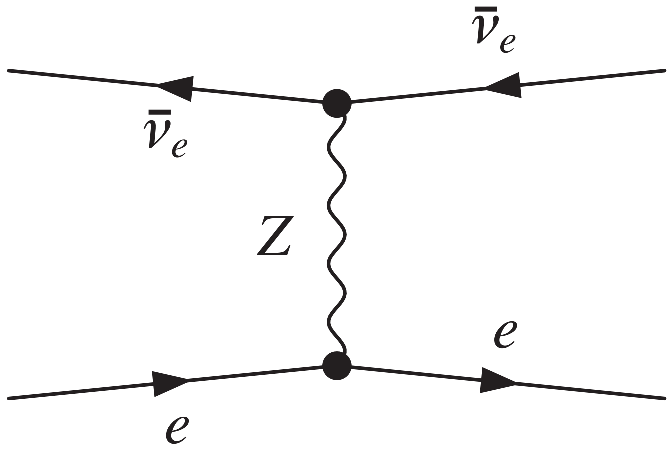
ANL, PRD 19, 2521 (1979)
ArgoNeuT, PRL 108, 161802 (2012)
BEBC, ZP C2, 187 (1979)
BNL, PRD 25, 617 (1982)
CCFR (1997 Seligman Thesis)
CDHS, ZP C35, 443 (1987)
GGM-SPS, PL 104B, 235 (1981)
GGM-PS, PL 84B (1979)
IHEP-ITEP, SJNP 30, 527 (1979)
IHEP-JINR, ZP C70, 39 (1996)
MINOS, PRD 81, 072002 (2010)
NOMAD, PLB 660, 19 (2008)
NuTeV, PRD 74, 012008 (2006)
SciBooNE, PRD 83, 012005 (2011)
SKAT, PL 81B, 255 (1979)
T2K, PRD 87, 092003 (2013)
σ_{CC} / E_ν (10^{-38} cm^2 / GeV)
ν_μ N → μ^- X
$\bar{\nu}_\mu$ N → μ^+ X
E_ν (GeV)

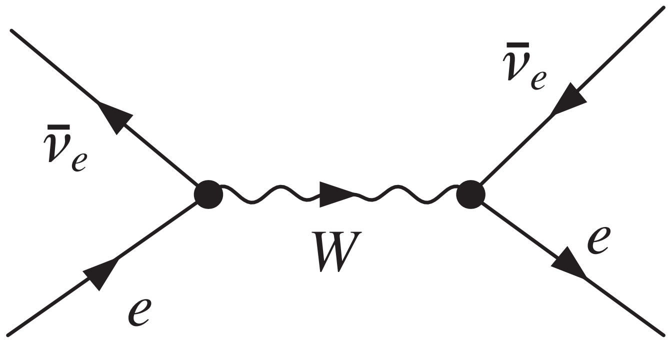


We now plot σ/E so we can see everything on the same scale. QE is quasi-elastic. RES is resonant where the proton is excited and DIS is inelastic scattering.

Neutral currents

Neutrinos can also interact via the exchange of a Z^0 boson. The couplings are a bit more complex. Here we show an antineutrino scattering from an electron, both currents come into play.





The Z^0 arises in the SM from a combination of W^0 and B bosons in $SU(2) \times U(1)$ breaking. As a result it mixes couplings.

It couples to both electromagnetic charge and weak isospin:

$$g_V^i = t_3^i - 2Q_i \sin^2\theta_W$$

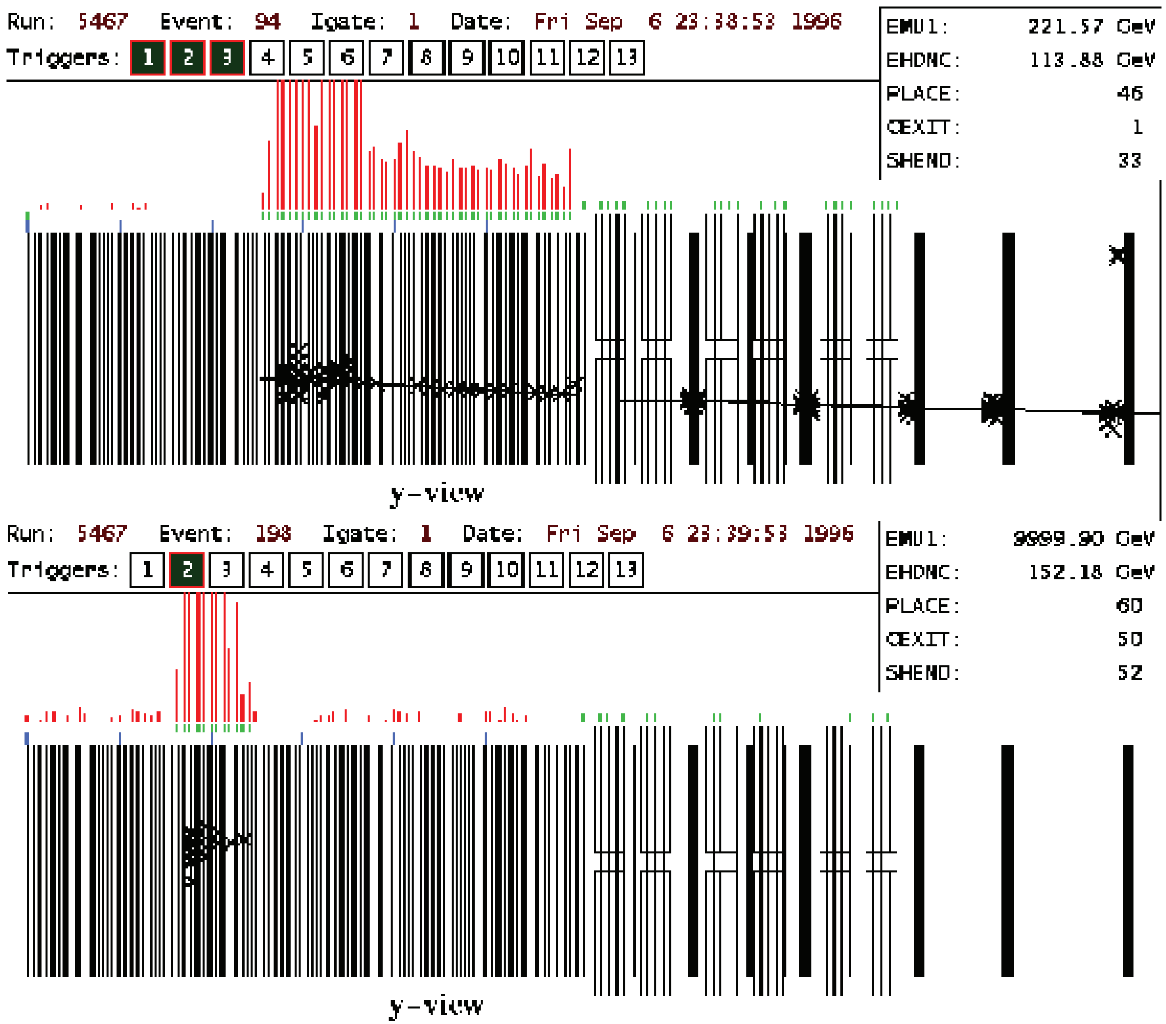
$$g_A^i = t_3^i$$

and the vertex terms look like

$$-\frac{g}{2\cos\theta_W}\gamma^\mu(g_V^i + \gamma^5 g_A^i)$$

Because Z_0 scattering depends on $\sin^2\theta_W$ differently than W scattering, you can compare the two processes to get

$$R = \frac{\sigma^{\nu}_{NC} - \sigma^{\overline{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\overline{\nu}}_{CC}} \simeq \frac{1}{2} - \sin^2\theta_W$$



Charged (top) and Neutral (bottom) scattering events in the NuTeV neutrino detector.

Quantum numbers

Particle	EM charge	Strong Charge	Weak Isospin	g_V^i
ν_e, ν_μ, ν_τ	0	0	$\frac{1}{2}, +\frac{1}{2}$	0.50
e, μ, τ	-1	0	$\frac{1}{2}, -\frac{1}{2}$	-0.054
u, c, t quark	$+\frac{2}{3}$	red,green or blue	$\frac{1}{2}, +\frac{1}{2}$	0.20
d, s, b quark	$-\frac{1}{3}$	red, green or blue	$\frac{1}{2}, -\frac{1}{2}$	-0.35
γ	0	0	0, 0	
$W^\pm$	± 1	0	$1, \pm 1$	
Z^0	0	0	1, 0	
Gluon	0	color a + anti-color b	0, 0	

The Z^0 likes to couple to neutrinos quite a lot!