NEUTRINO PHYSICS – ENTERING THE ERA OF PRECISION MEASUREMENTS

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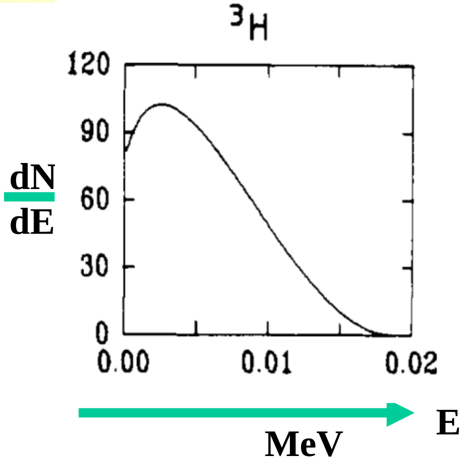
Lecture 1: Neutrino properties & interactions

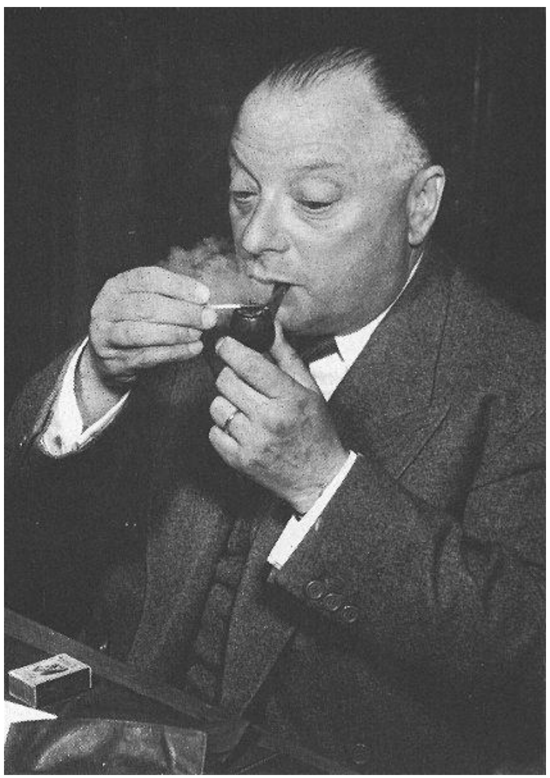
Lecture 2: Neutrino oscillations

1930 Neutrinos: *the birth of the idea*

Pauli's letter of the 4th of December 1930

e^- spectrum in beta decay





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 Li6 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 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous 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...

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant

. W. Pauli

translation: L.M. Brown, Phys. Today, Sept.1978, 23

Wolfgang Pauli

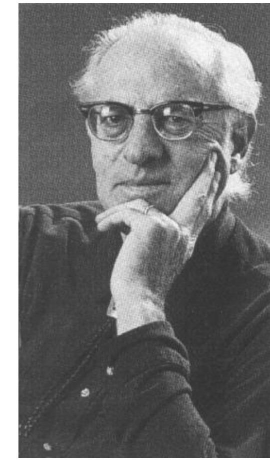
Reines and Cowan **1953**

Neutrinos: *direct detection*

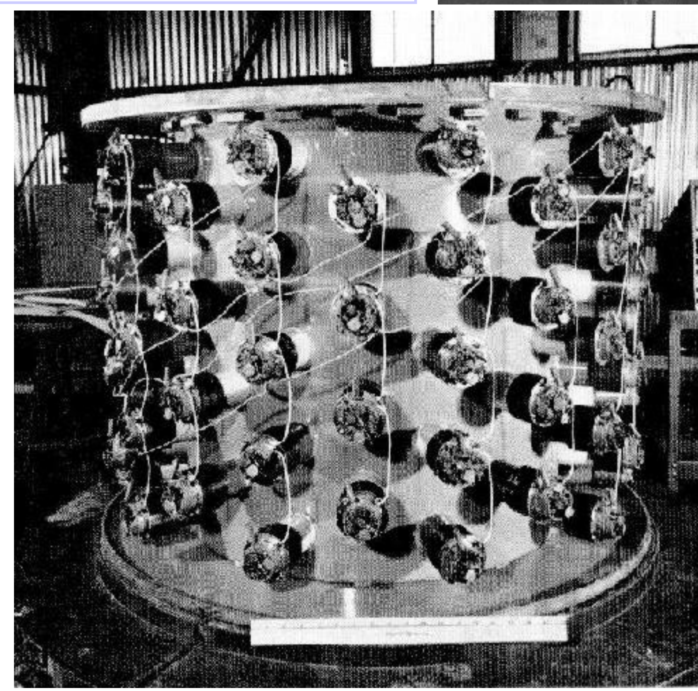
The anti-neutrino coming from the nuclear reactor interacts with a proton of the target, giving a positron and a neutron.

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

The target is made of about 400 liters of water mixed with cadmium chloride



The positron annihilates with an electron of target and gives two simultaneous photons ($e^+ + e^- \rightarrow \gamma\gamma$) **.**
The neutron slows down before being eventually captured by a Cd nucleus, that gives the emission of 2 photons about 15 microseconds after those of the positron.



All those 4 photons are detected and the 15 microseconds identify the "neutrino" interaction.

4-fold delayed coincidence

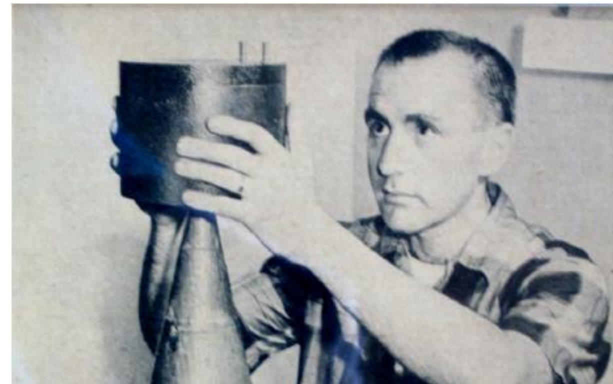
Neutrinos: *two-component theory*

1956 Parity violation in ^{60}Co beta d
(C.S. Wu et al)

1957 Neutrino helicity measurement
Sunyar): neutrinos have <u>negat</u>
γ polarization is detected by abs
(reversibly) magnetized iron

$$e^- + \mathrm{Gd} \to \nu_e + \mathrm{Sm}^*$$
$$\downarrow$$
$$\mathrm{Sm} + \gamma$$

Science and Jazz in the NY Daily News
Sunday September 21, 1958



1959 Ray Davis established that (anti) neutrinos from reactors do with chlorine to produce argon

reactor : n → p e^- ν_e or $\bar{\nu}_e$?

these ν_e do not do

they are anti-neutrinos

Neutrinos: *their properties*

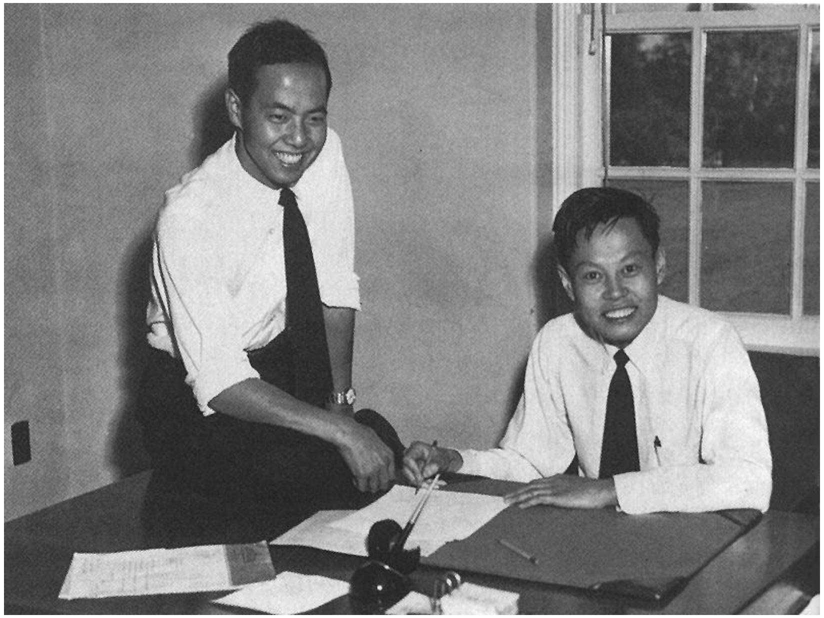
1960

In 1960, Lee and Yang realized that if a reaction like

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

is not observed, this is because two types of neutrinos exist ν_μ and ν_e

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



Lee and Yang

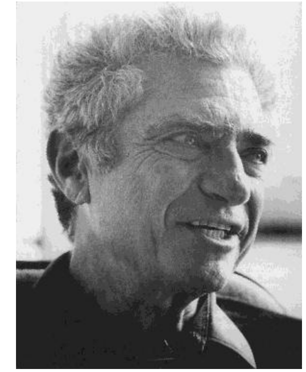
otherwise $\mu^- \rightarrow e^- + \nu + \bar{\nu}$ has the same Quantum numbers as $\mu^- \rightarrow e^- + \gamma$

Two Neutrinos

1962

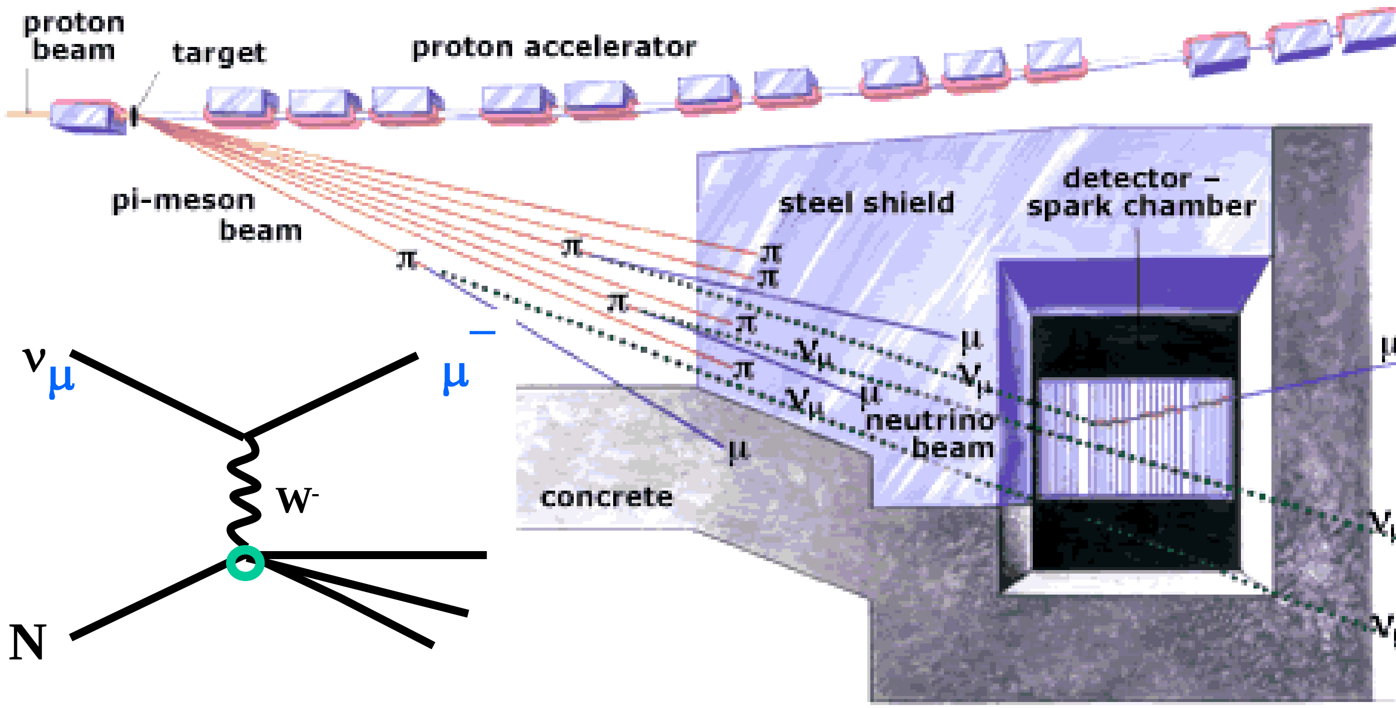
Schwartz

Lederman



Steinberger

AGS Proton Beam

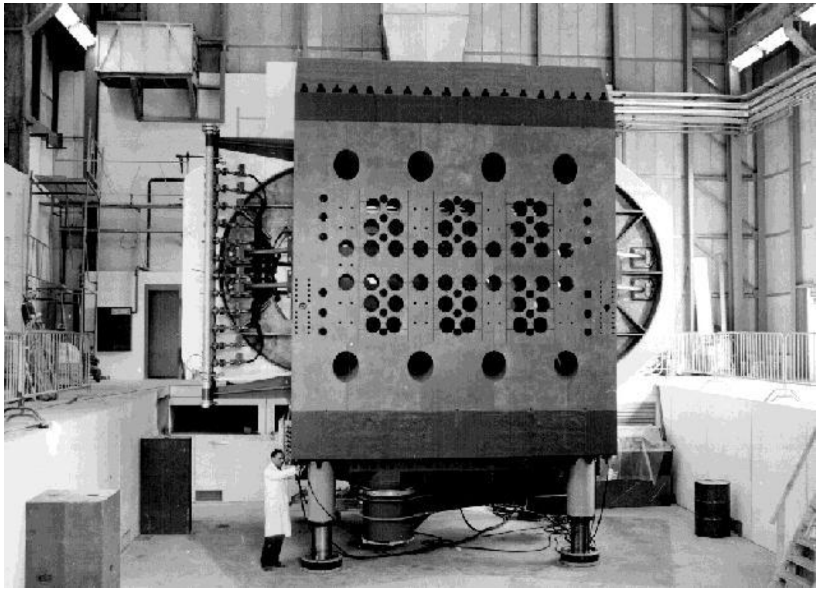


Neutrinos from π-decay only produce muons (not electrons)

when they interact in matter

Neutrinos

the weak neutral current



Gargamelle Bubble Chamber
CERN

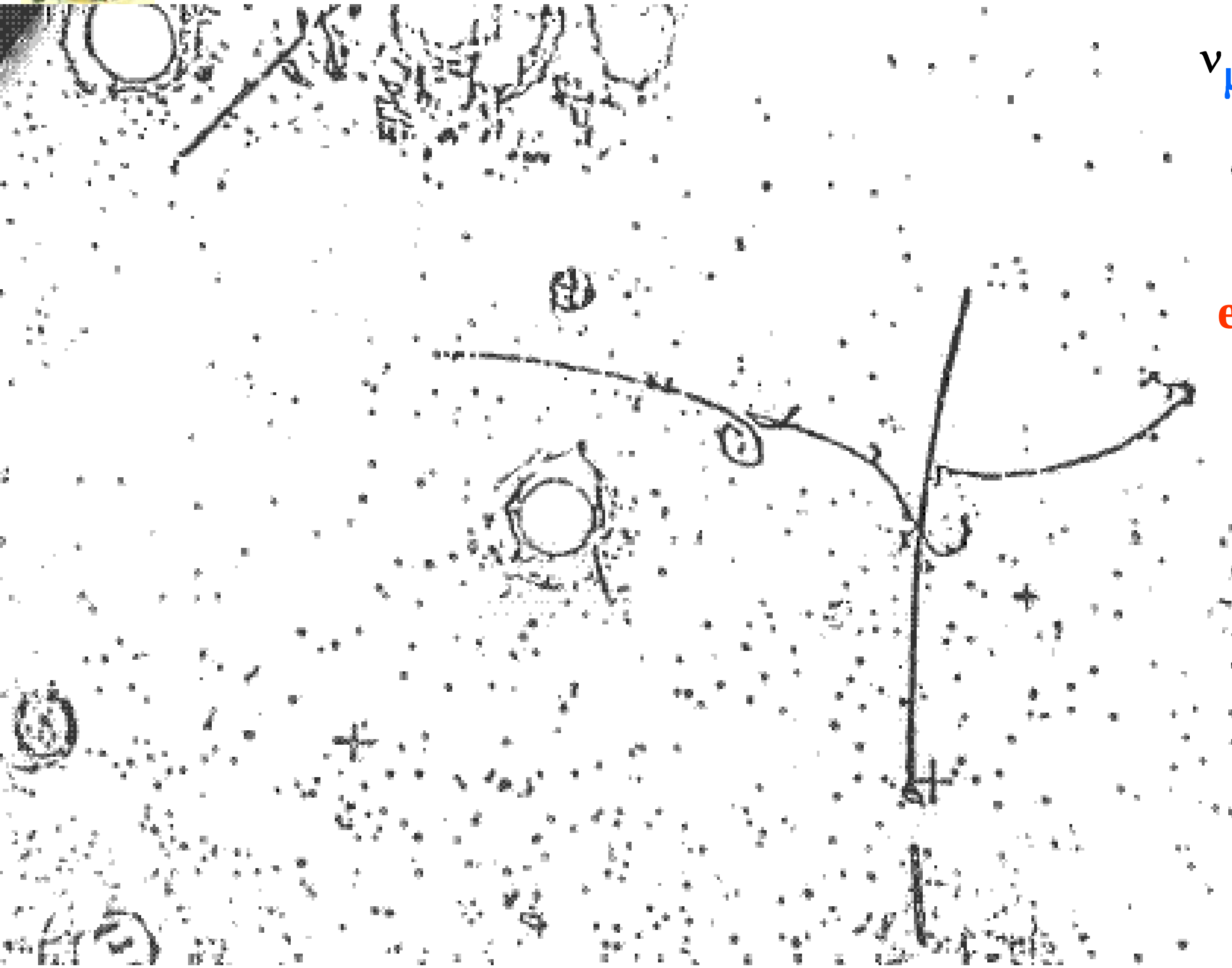
Discovery of weak neutral current

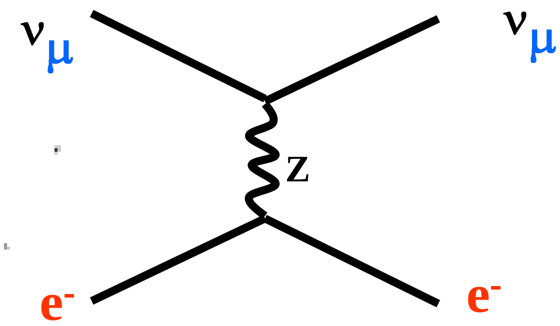
$\nu_\mu + e \rightarrow \nu_\mu + e$

$\nu_\mu + N \rightarrow \nu_\mu + X$ (no muon)

Previous searches for neutral currents had been performed in particle decays (e.g. $K^0 \rightarrow \mu\mu$) leading to extremely stringent limits (~10^{-7}).

Early neutrino experiments had set their trigger on final state (charged) lepton!





elastic scattering of neutrino off electron in the liquid

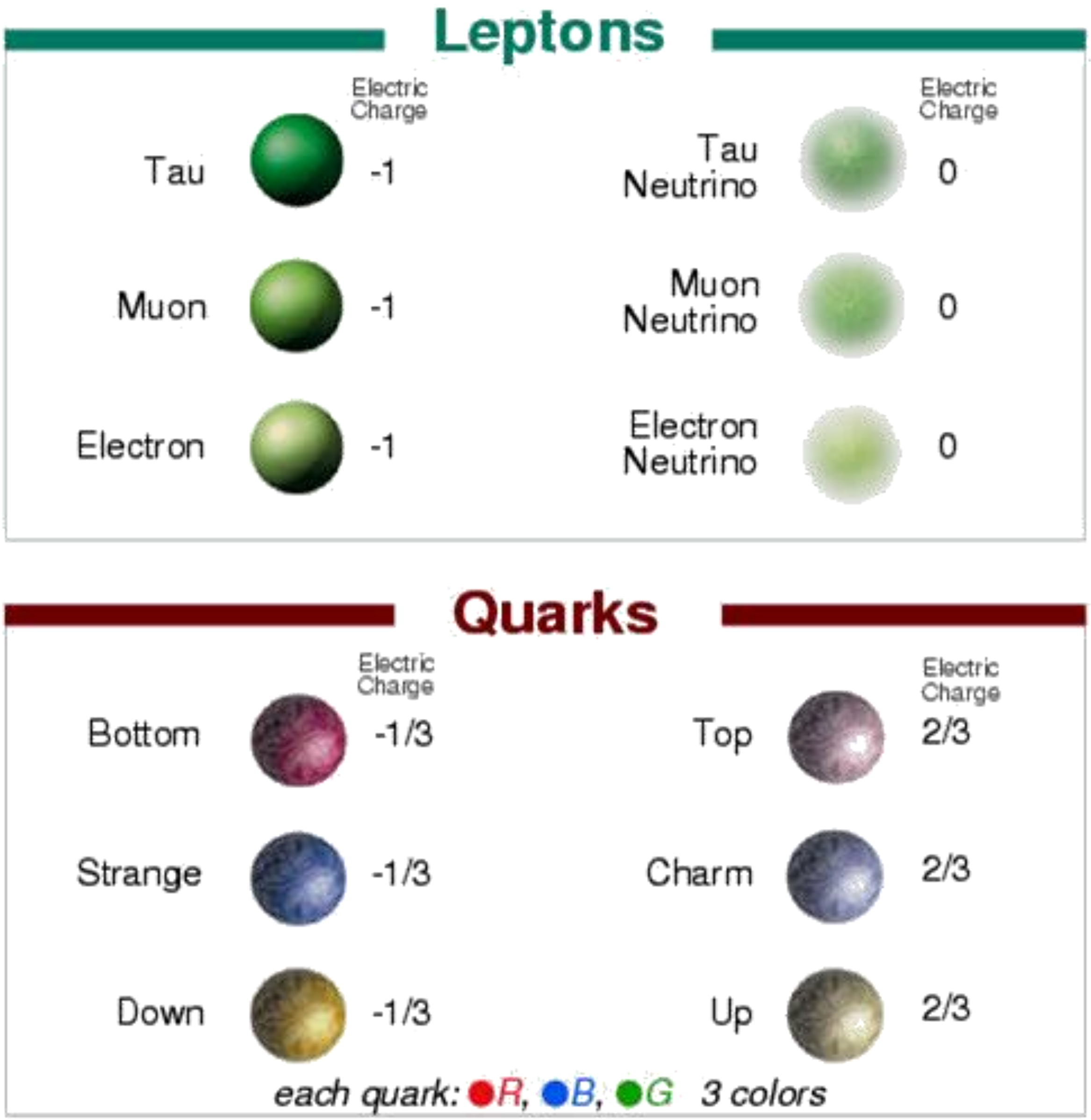
1973 Gargamelle

experimental birth of the Standard model

The Standard Model of fundamental particles and interactions

3 families of spin ½ quarks and leptons interacting by exchanging of spin 1 vector bosons (γ, $W^{\pm}$, Z^0, 8 gluons)

charged leptons	e	μ	τ
	mc^2=0.0005 GeV	0.106 GeV	1,78 GeV
neutral leptons (neutrinos)	ν_e	ν_μ	ν_τ
	mc^2 <1 eV	<1 eV	<1 eV
quarks	d	strange	beauty
	mc^2=0.005 GeV	0.1 GeV	4.2 GeV
	u	charm	top
	mc^2=0.0025 GeV	1.5 GeV	171 GeV
	First family	Second family	Third family

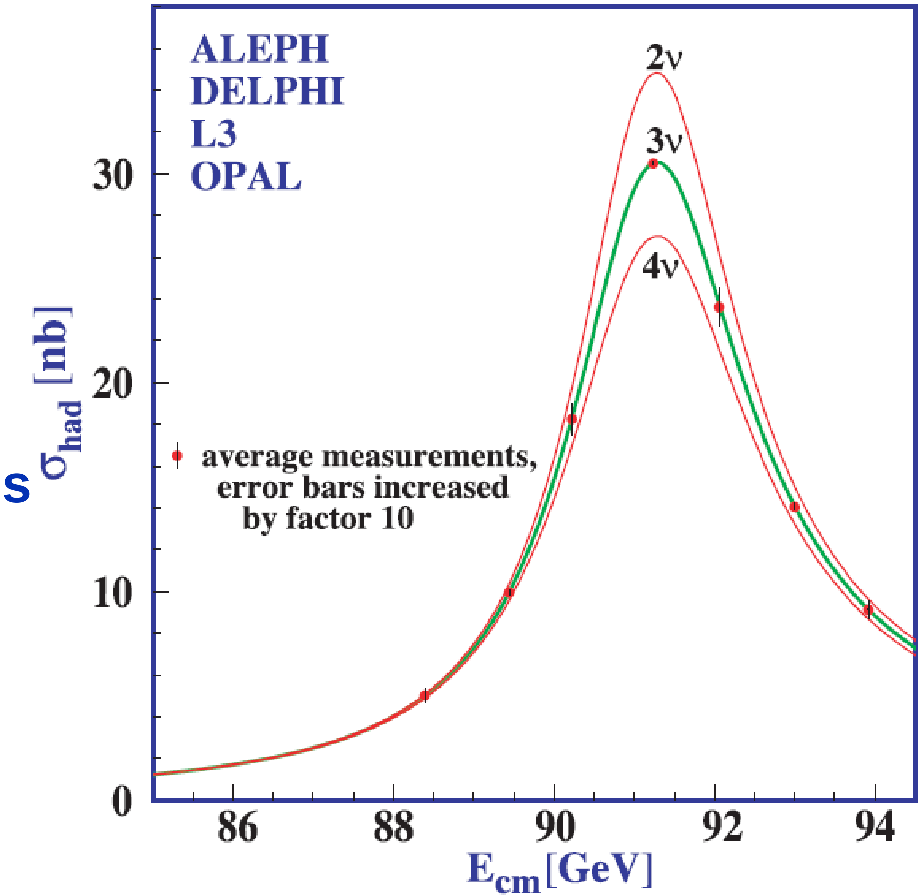


The particle drawings are simple artistic representations

The number of neutrinos (generations)

collider experiments: LEP

- N_ν determined from the visible Z cross-section at the peak (most of which is due to its coupling to hadrons):
the more decays are invisible the fewer are visible:
hadron cross section decreases by 13% for one more family of neutrinos



in 2001: N_ν = 2.984 ±0.008

ν in the SM

- The SM is a gauge theory based on the symmetry group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

- LEP tested this symmetry to 1% precission and the missing particles t, ν_τ were found confirming 3 family structure

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

There is no ν_R

$\Rightarrow$ Accidental global symmetry:

$B \times L_e \times L_\mu \times L_\tau$

$\Rightarrow$ **ν *strictly* massless**

Weak interaction: current *x* current

$$\mathcal{L} = -e\left\{A_\mu J_{em} + \frac{1}{\sqrt{2}\sin\theta_W}(W_\mu^+ \bar{\nu}_{eL}\gamma^\mu e_L + W_\mu^- \bar{e}_L\gamma^\mu \nu_{eL}) + \frac{1}{\sin\theta_W\cos\theta_W} Z_\mu J_{NC}^\mu\right\}$$

$$J_{em}^\mu = -\bar{e}_L\gamma^\mu \mathrm{e}_L - \bar{e}_R\gamma^\mu \mathrm{e}_R = -\bar{e}\gamma^\mu e$$

$$J_{NC}^\mu = \tfrac{1}{2}\bar{\nu}_{eL}\gamma^\mu \nu_{eL} - \tfrac{1}{2}\bar{e}_L\gamma^\mu \mathrm{e}_L - \sin^2\theta_W J_{em}^\mu$$

Weak interaction: mass term

$$
\begin{aligned}
\mathcal{L}_{\text{Yuk}} &= -c_e \bar{e}_R \phi^\dagger \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} + h.c. \\
&= -c_e \left[\bar{e}_R \phi_0^\dagger \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} + (\bar{\nu}_e, \bar{e}_L)\phi_0 e_R \right] \\
&= -c_e \left[\bar{e}_R \frac{1}{\sqrt{2}} v e_L + \bar{e}_L \frac{1}{\sqrt{2}} v e_R \right] \\
&= -c_e v \frac{1}{\sqrt{2}} (\bar{e}_R e_L + \bar{e}_L e_R) \\
&= -c_e \frac{v}{\sqrt{2}} \bar{e} e .
\end{aligned}
$$

There is no such term for the neutrinos, because they do not have right components

Electron mass: $m_e = c_e \dfrac{v}{\sqrt{2}}$

Weak interaction: mixing of down quarks

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \times \begin{pmatrix} d \\ s \\ b \end{pmatrix} = U \times \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$

[PDG2008]

Total neutrino cross section

Charged current (CC)

$$\nu_\mu + N \rightarrow \mu^- + X$$

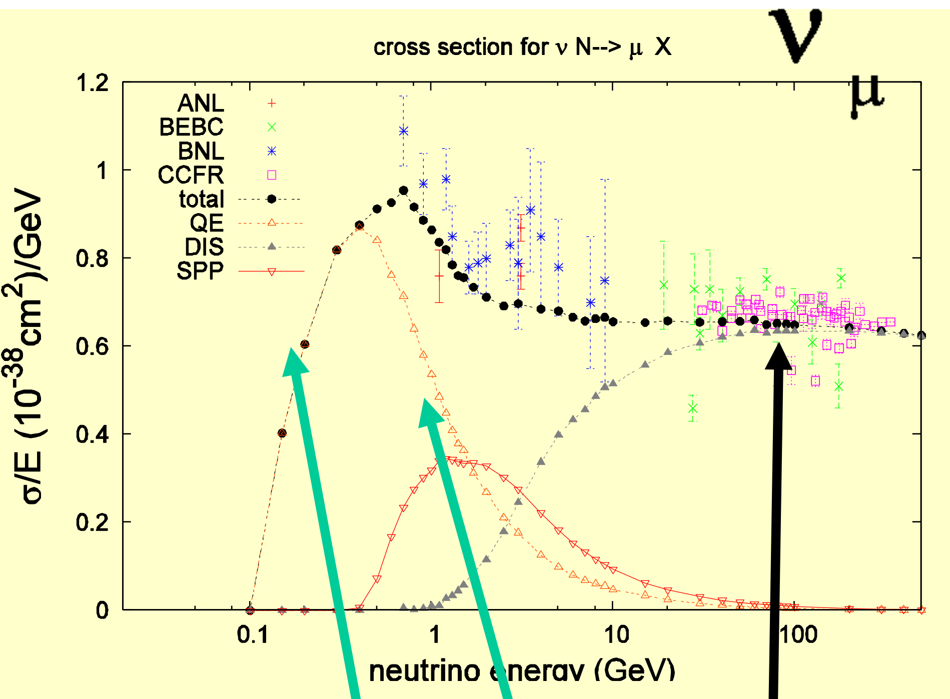
$$\tilde{\nu}_\mu + N \rightarrow \mu^+ + X$$

Neutral current (NC)

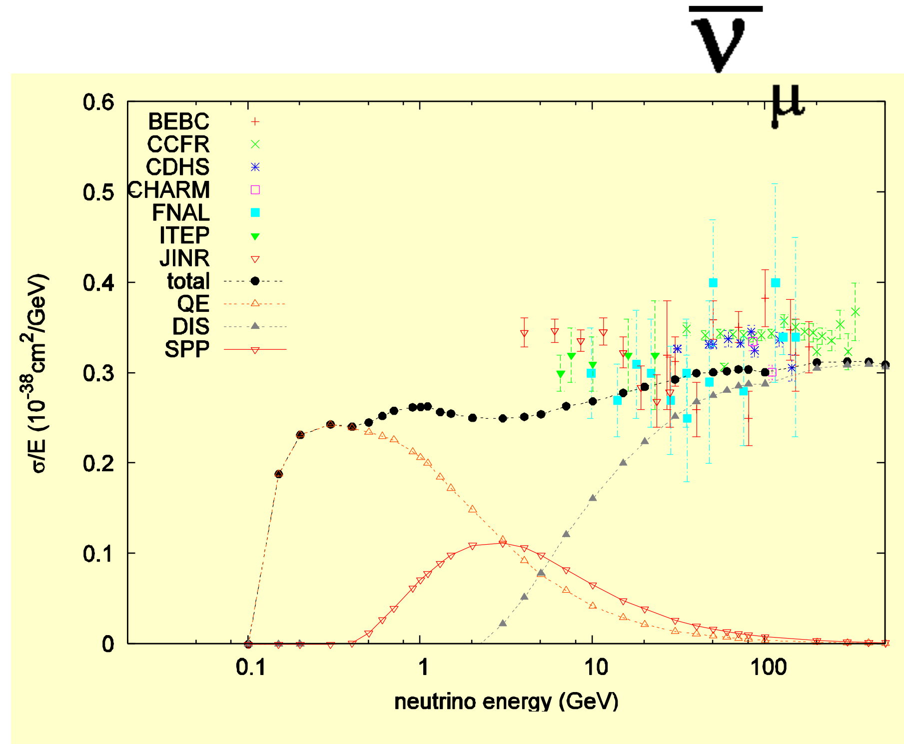
$$\nu_\mu + N \rightarrow \nu_\mu + X$$

$$\tilde{\nu}_\mu + N \rightarrow \tilde{\nu}_\mu + X$$

Total neutrino – nucleon CC cross section



neutrino



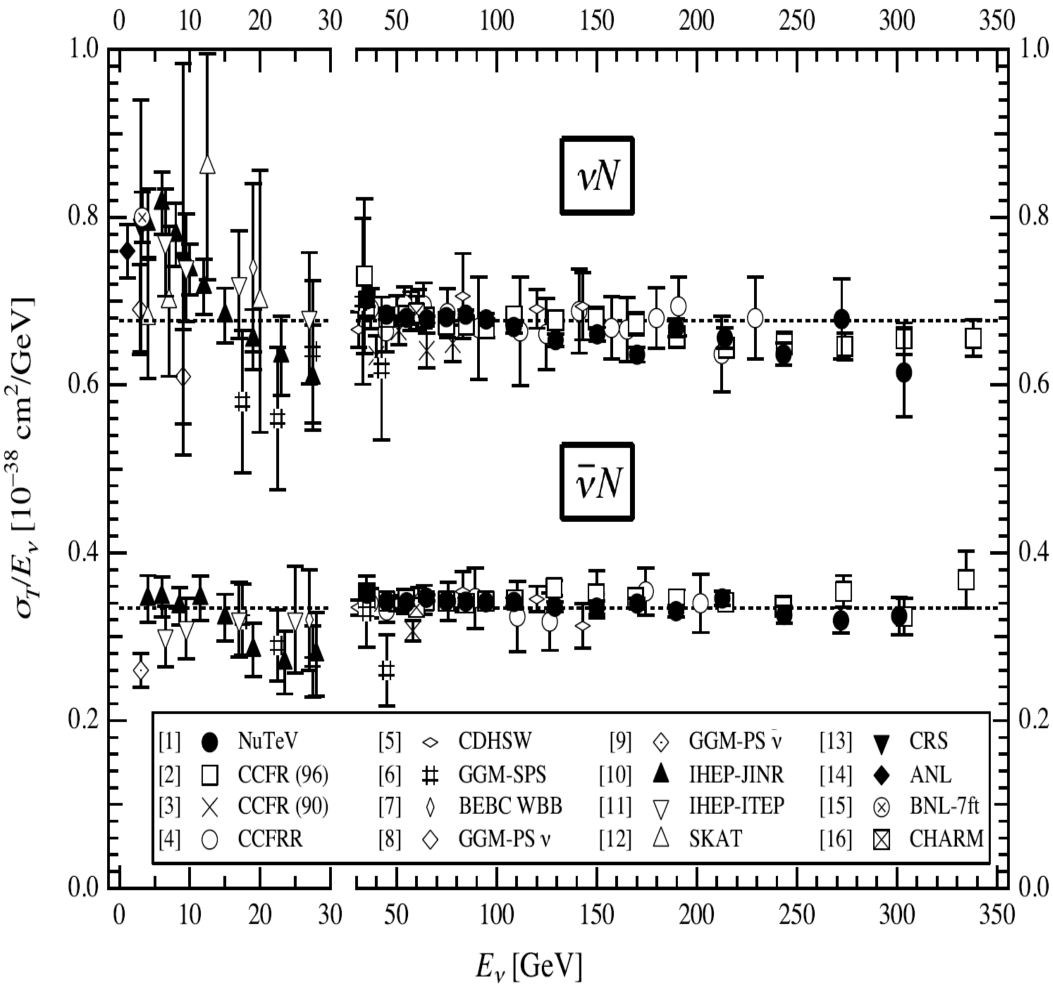
anti-neutrino

We distinguish:

- quasi-elastic
- single pion production („RES region", e.g. W<=2 GeV)
- more inelastic („DIS region")

σ_ν is very small: λ_{int} in water for 30 GeV neutrino is 8×10^{10}m (~ 0.55 AU) !

Total neutrino-nucleon cross section

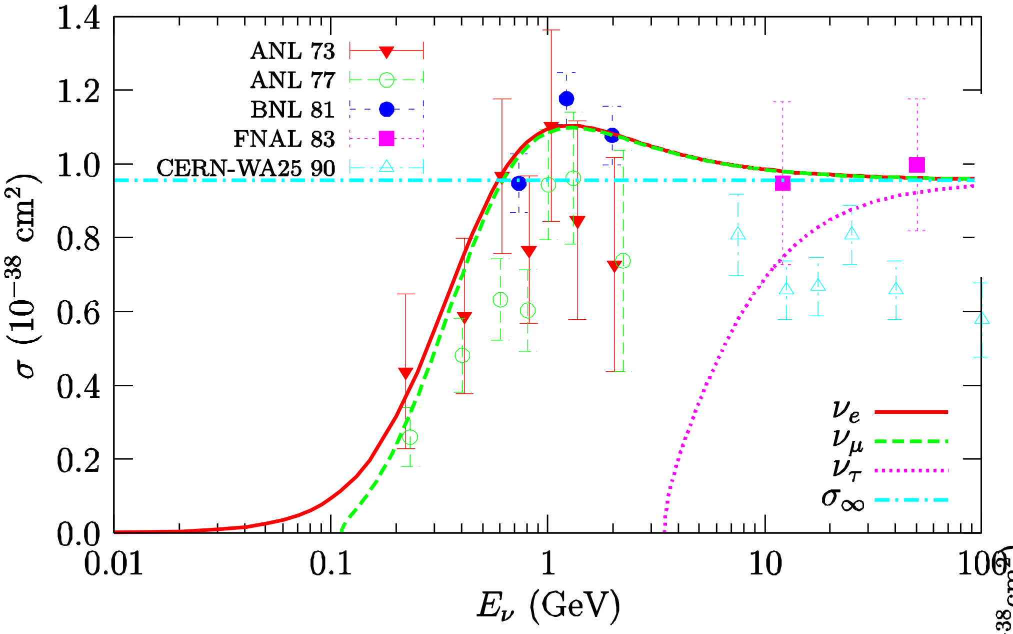


σ_T/E_ν = (0.677±0.014)x10^{-38} cm^2/GeV

[PDG2008]

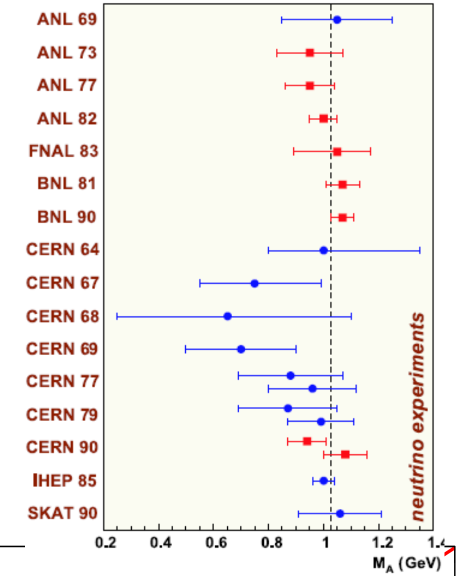
$\sigma_T/E_{anti-\nu}$ = (0.334±0.008)x10^{-38} cm^2/GeV

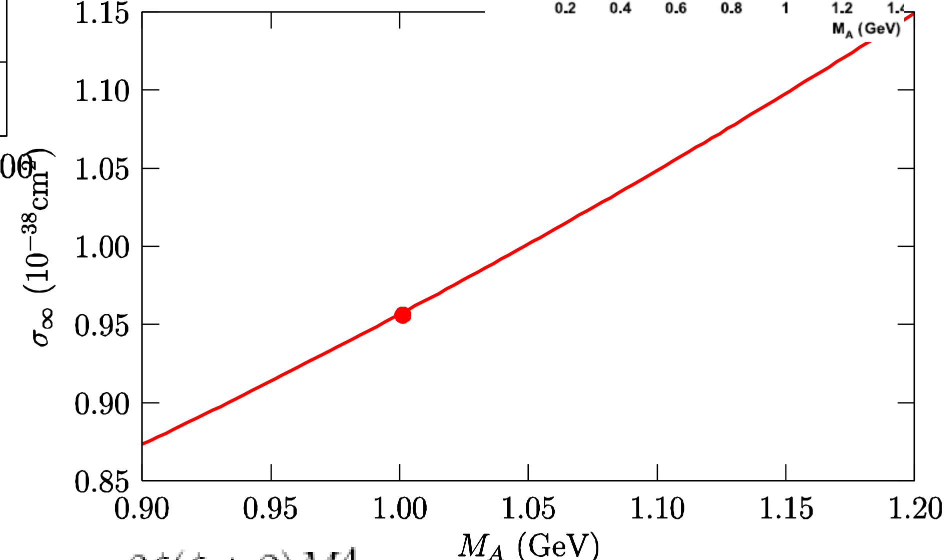
Quasi-elastic reaction



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

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





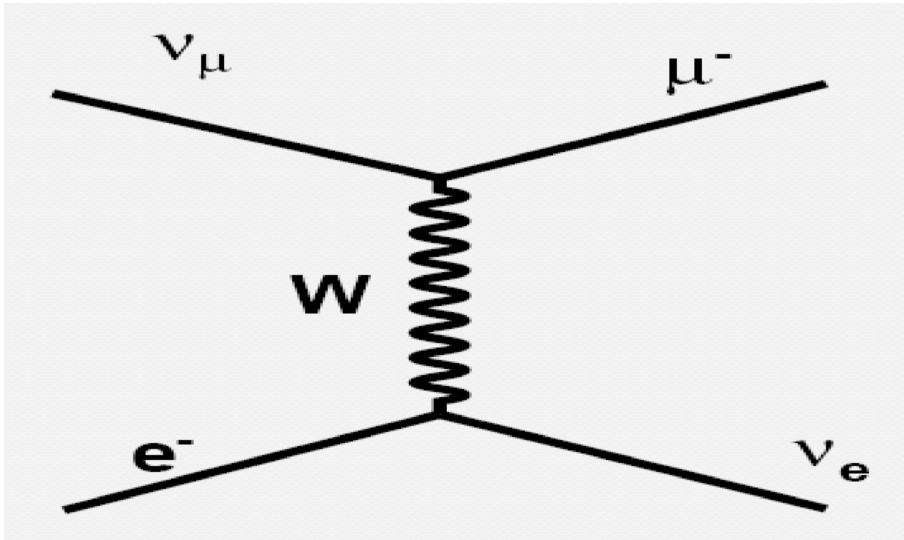
Huge experimental uncertainty

The limiting value depends on the axial mass

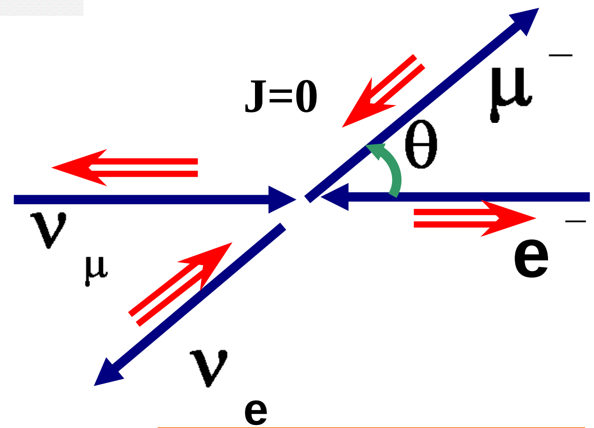
Under assumption of dipole vector form-factors:

$$\sigma_\infty = \frac{G_F^2 \cos^2\theta_C}{6\pi}\Big[M_V^2 + g_A^2 M_A^2 + \frac{2\xi(\xi+2)M_V^4}{(4M^2-M_V^2)^2}(M^2-M_V^2) + \frac{3\xi(\xi+2)M_V^8}{(4M^2-M_V^2)^3}\Big(\frac{4M^2}{4M^2-M_V^2}\ln\frac{4M^2}{M_V^2}-1\Big)\Big].$$

Quasielastic scattering off electrons



$$\nu_\mu + e^- \rightarrow \nu_e + \mu^-$$



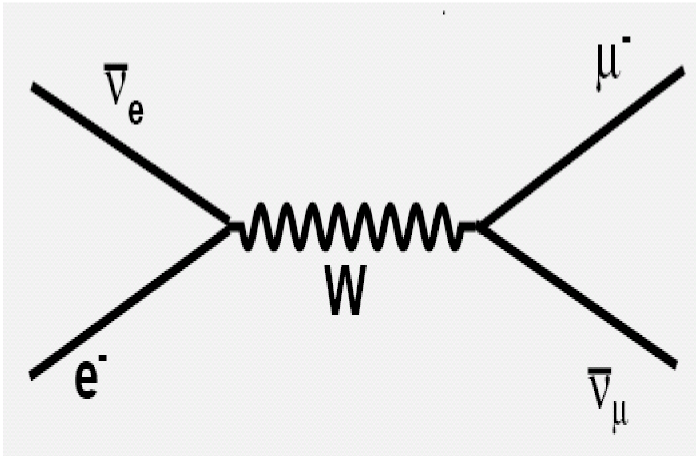
J=0 ==> Cross section is isotropic in c.m. system

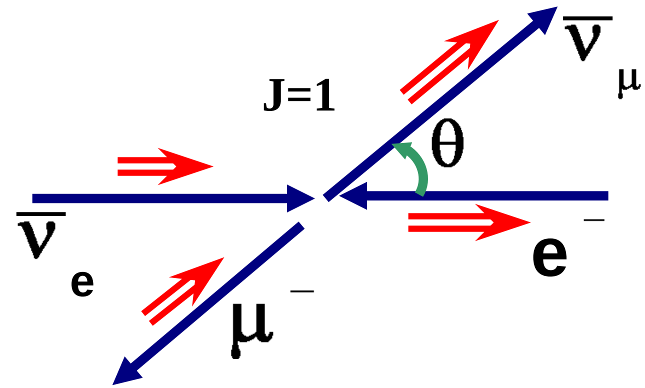
$$\sigma = \frac{G_F^2}{\pi} \frac{\left(s - m_\mu^2\right)^2}{s}$$

high energy limit (neglect muon mass)

$$\sigma = \frac{G_F^2}{\pi} s$$

Quasi-elastic scattering off electrons





$$\overline{\nu}_e + e^- \rightarrow \overline{\nu}_\mu + \mu^-$$

Differential cross section in c.m. system

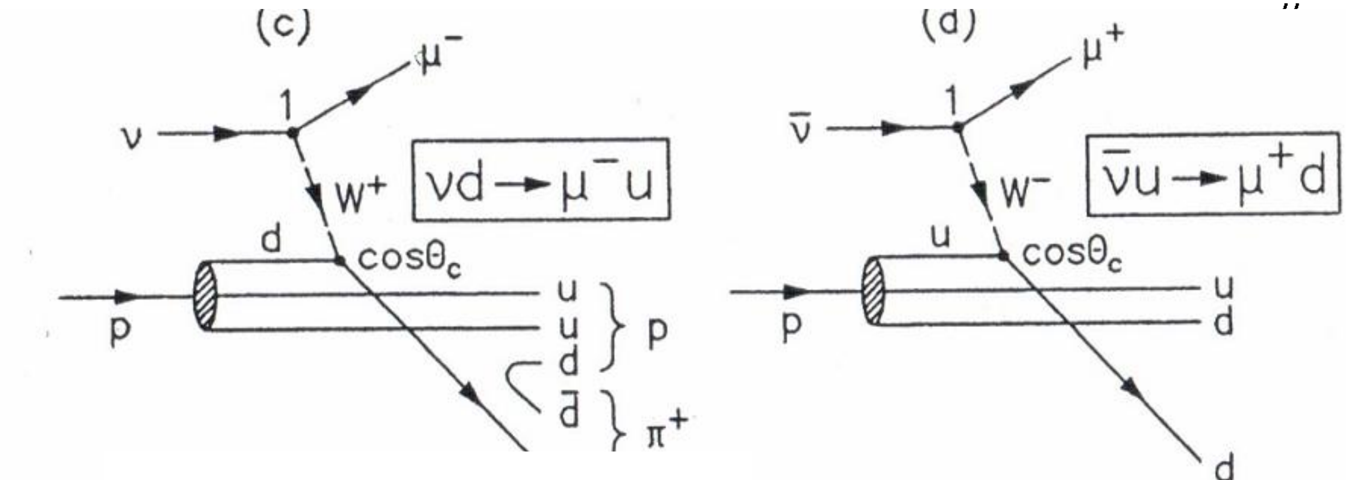
$$\frac{d\sigma}{d\cos\theta} = \frac{2G_F^2}{\pi} \frac{\left(s - m_\mu^2\right)^2 E_e E_\mu}{s^2} \left(1 + \frac{s - m_e^2}{s + m_e^2} \cos\theta\right)\left(1 + \frac{s - m_\mu^2}{s + m_\mu^2} \cos\theta\right)$$

Total cross section

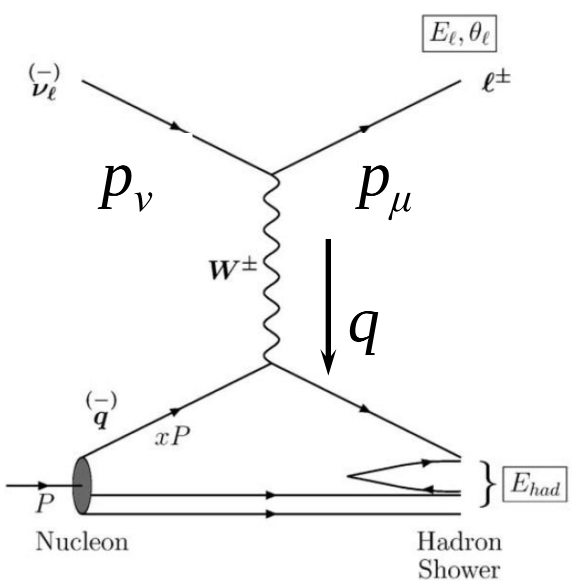
$$\sigma = \frac{2G_F^2}{\pi} \frac{\left(s - m_\mu^2\right)^2 \left(E_e E_\mu + 1/3 E_{\nu 1} E_{\nu 2}\right)}{s^2}$$

Quark-parton picture

$$\nu_{\mu} + N \rightarrow \mu^{-} + X$$



$$q^2 = (p_\nu - p_\mu)^2 = -Q^2 < 0$$

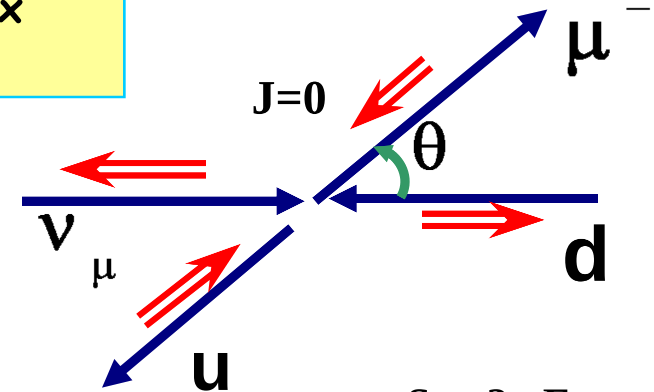


$$\nu = E_\nu - E_\mu = E_{had} - M_N = (q.\, p_{had})/M_N$$

$$x_{Bjorken} = \frac{-\tilde{q}^{\,2}}{2\tilde{q}\,.\,\tilde{p}_{had}} = \frac{Q^2}{2M\nu}$$

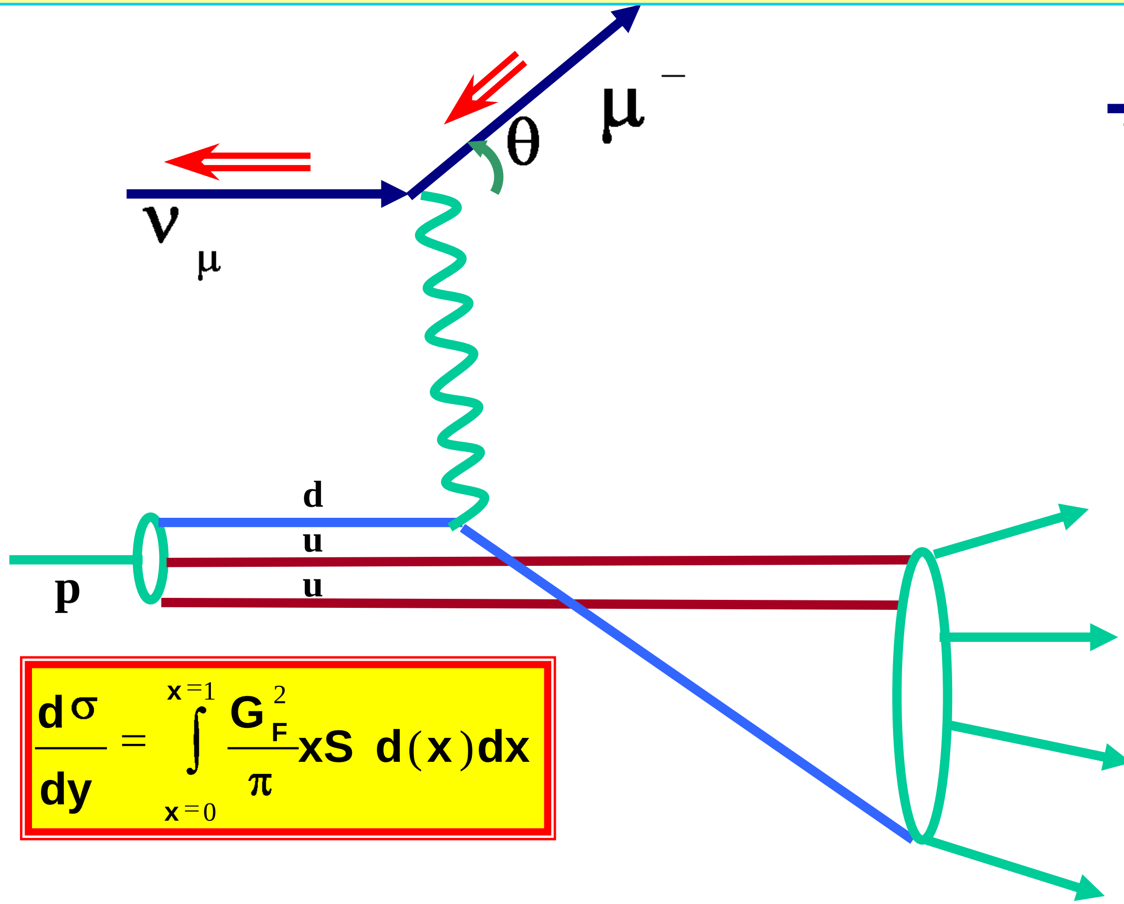
At high energies interactions on quarks dominate: DIS regime: neutrinos on (valence) quarks

x= fraction of longitudinal momentum carried by struck quark
y= (1-cosθ)/2
for J=0 isotropic distribution
d(x)= probability density of quark d with mom. fraction x
<u>All masses neglected!</u>



$s = xS = 2mE_\nu x$

$$\frac{d\sigma(x)}{dy} = \frac{G_F^2}{\pi} xS$$

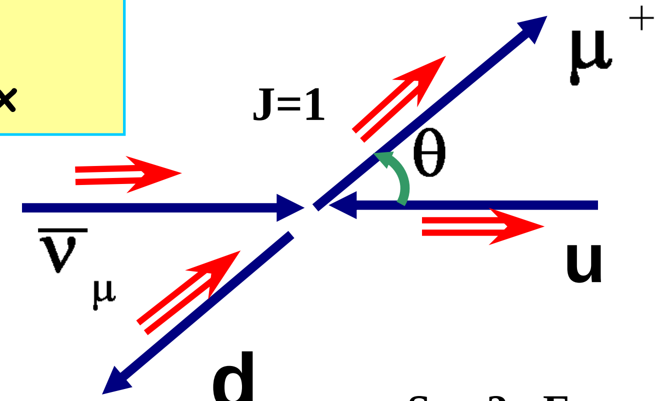


$$\frac{d\sigma}{dy} = \int_{x=0}^{x=1} \frac{G_F^2}{\pi} xS\ d(x)dx$$

multi-hadron system
with the right quantum number

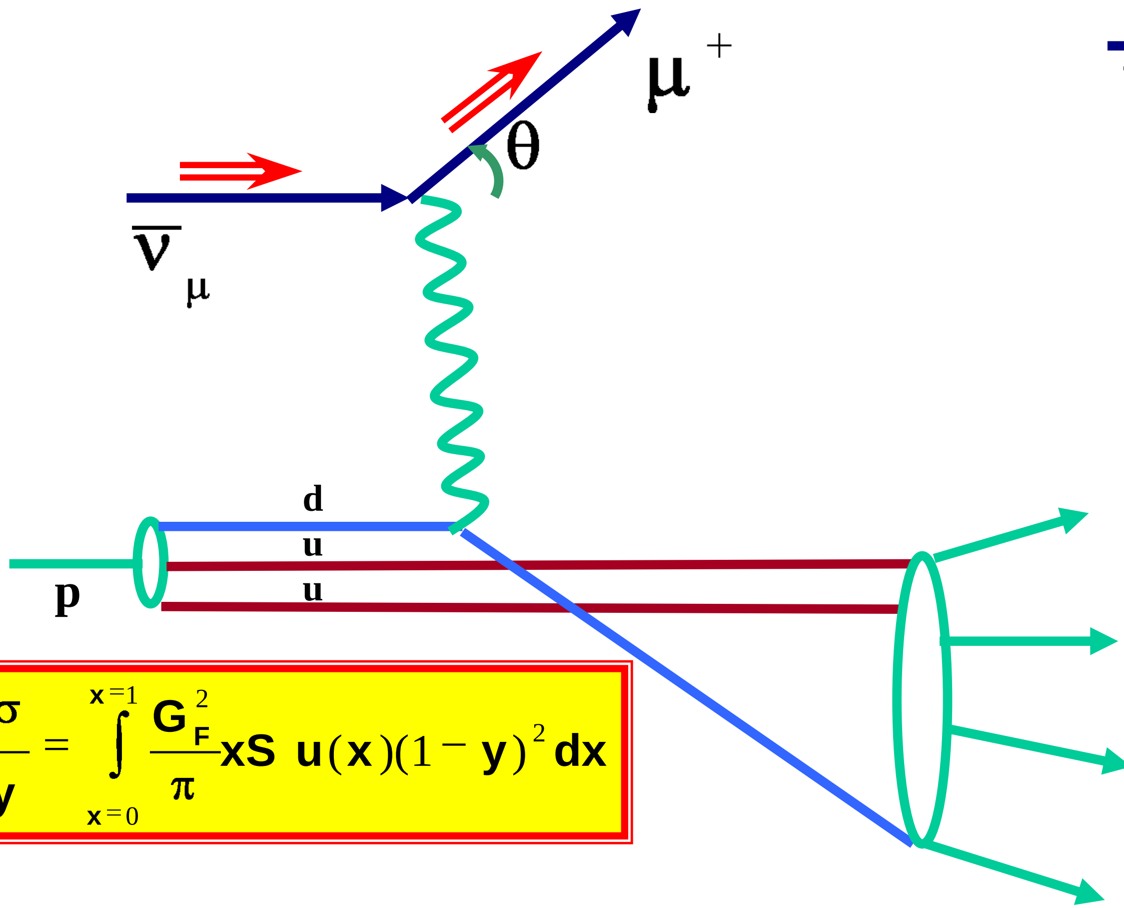
At high energies interactions on quarks dominate: DIS regime: anti-neutrinos on (valence) quarks

x= fraction of longitudinal momentum carried by struck quark
$y = (1-\cos\theta)/2$
for J=1 distribution prop. to $(1-y)^2$ (forward favored)
u(x)= probability density of quark u with mom. fraction x



$s = xS = 2mE_\nu x$

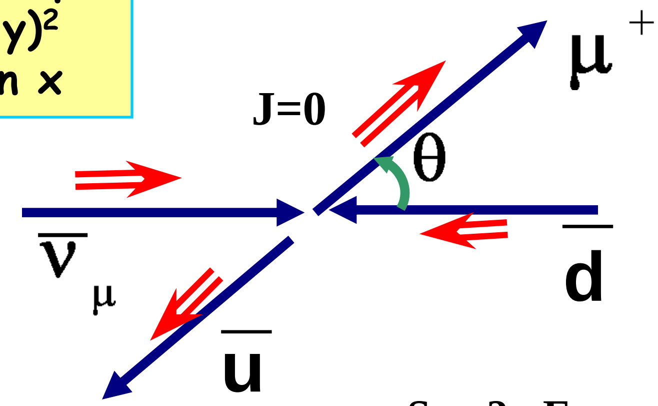
$$\frac{d\sigma(x)}{dy} = \frac{G_F^2}{\pi} xS\ (1-y)^2$$



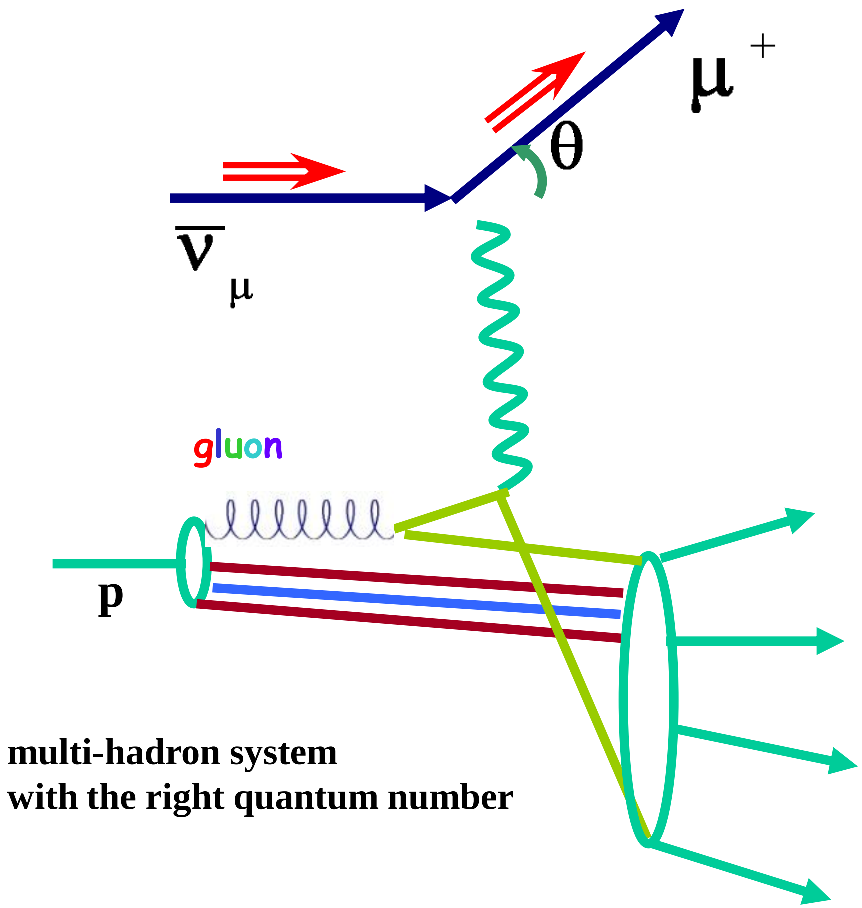
$$\frac{d\sigma}{dy} = \int_{x=0}^{x=1} \frac{G_F^2}{\pi} xS\ u(x)(1-y)^2\, dx$$

There are also gluons and anti-quarks at low x (sea)
(anti)neutrinos on sea-(anti)quarks

for J=0 (neutrino+quarks or antineutrino+antiquarks) isotropic
for J=1 (neutrino+antiquarks or antineutrino+quarks) $(1-y)^2$
$q_i(x)$, = probability density of quark u with mom. fraction x



$$s = xS = 2mE_\nu x$$



$$\frac{d\sigma^{\nu}}{dy} = \int_{x=0}^{x=1} \frac{G_F^2}{\pi} xS\,\left(\bar{q}(x)(1-y)^2 + q(x)\right)dx$$

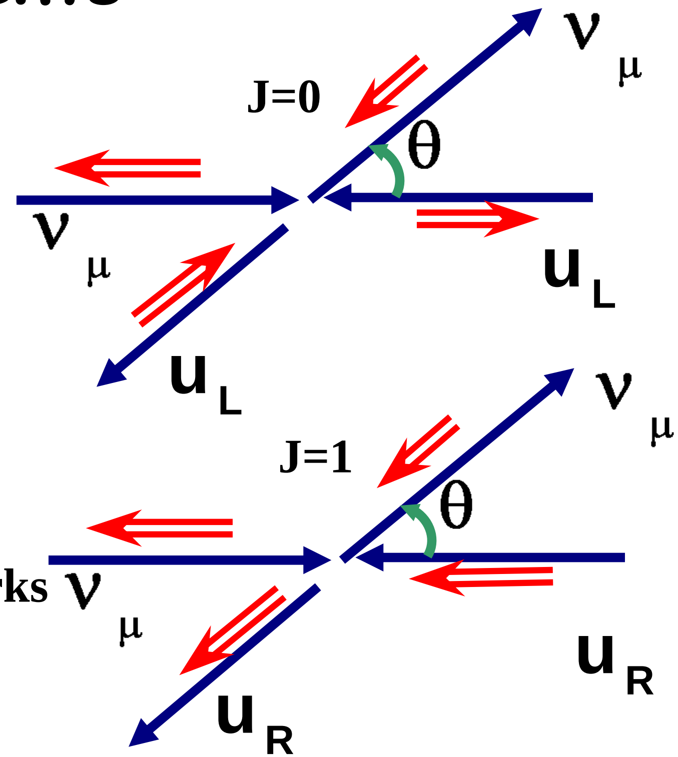
$q = d, s, (b)$ and $\bar{q} = \bar{u}, \bar{c}, (\bar{t})$

$$\frac{d\sigma^{\bar{\nu}}}{dy} = \int_{x=0}^{x=1} \frac{G_F^2}{\pi} xS\,\left(q(x)(1-y)^2 + \bar{q}(x)\right)dx$$

$q = u, c, (t)$ and $\bar{q} = \bar{d}, \bar{s}, (\bar{b})$

Neutral Currents

Electroweak theory



CC: $g = e/\sin\theta_W$
NC: $g' = e/\sin\theta_W\cos\theta_W$

NC fermion coupling = $g'(I^3 - Q\sin^2\theta_W)$

I^3= weak isospin =
+1/2 for Left handed neutrinos & u-quarks,
-1/2 for Left handed electrons, muons, taus, d-quarks
0 for right handed leptons and quarks

Q= electric charge
θ_W= weak mixing angle.

$$g_L^u = 1/2 - 2/3\sin^2\theta_W$$

$$g_R^u = \quad - 2/3\sin^2\theta_W$$

$$\frac{d\sigma(x)}{dy} = \frac{G_F^2\rho^2}{\pi} xS\left(g_L^{u\,2} + g_R^{u\,2}(1-y)^2\right)$$

(sum over quarks and antiquarks as appropriate)

the parameter ρ can be calculated by remembering that for these cross sections we have the W (resp Z) propagator, and that the CC/NC coupling is in the ratio $\cos\theta_W$
thus $\rho^2 = m_W^4/(m_Z^4\cos\theta_W) = 1$ at tree level in the SM,
but is affected by radiative corrections sensitive to e.g. m_{top}

Structure functions

The matrix element of νN interaction:

$$\Im = \sqrt{2}G_F \times \frac{1}{1+\frac{Q^2}{M_W^2}} \times L^{\mu} \times H_{\mu}$$

$$H^{\alpha\beta} = \sum_X \langle p|J^{\alpha}|X\rangle\langle X|J^{\beta}|p\rangle = -\frac{g^{\alpha\beta}}{M} F_1^{\nu(\bar{\nu})N} + \frac{p^{\alpha}p^{\beta}}{\nu M^2} F_2^{\nu(\bar{\nu})N} - \frac{i\epsilon^{\alpha\beta\gamma\delta}p_{\gamma}q_{\delta}}{2\nu M^2} F_3^{\nu(\bar{\nu})N}.$$

Structure functions

$$\frac{d^2\sigma^{\nu(\bar\nu)N}}{dx\,dy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left[y^2 x F_1^{\nu(\bar\nu)N} + (1-y)F_2^{\nu(\bar\nu)N} \pm \left(1-\frac{y}{2}\right) y x F_3^{\nu(\bar\nu)N}\right]$$

$$\frac{d\sigma^{\nu(\bar\nu)h}(P,q)}{dE_\mu d\Omega_\mu} = \sum_q \int_0^1 dx \, \frac{d\sigma^{\nu(\bar\nu)q}(xP,q)}{dE_\mu d\Omega_\mu}\left(q_h(x)+\bar q_h(x)\right)$$

$$F_2^{\nu(\bar\nu)N}(x) = 2xF_1^{\nu(\bar\nu)N}(x) = x[u(x)+\bar u(x)+d(x)+\bar d(x)+s(x)+\bar s(x)+c(x)+\bar c(x)]$$

$$xF_3^{\nu N}(x) = x[u_v(x)+d_v(x)+2(s(x)-c(x))] \, ,$$

$$xF_3^{\bar\nu N}(x) = x[u_v(x)+d_v(x)-2(s(x)+c(x))] \, ,$$

$$q_v(x) = q(x) - \bar q(x) \quad q \in \{u, d\}$$

Sum rules for e.g. the proton

$$\int_0^1 u_V(x)\,dx = \int_0^1 [u(x)-\bar u(x)]\,dx = 2$$

$$\int_0^1 d_V(x)\,dx = \int_0^1 [d(x)-\bar d(x)]\,dx = 1.$$

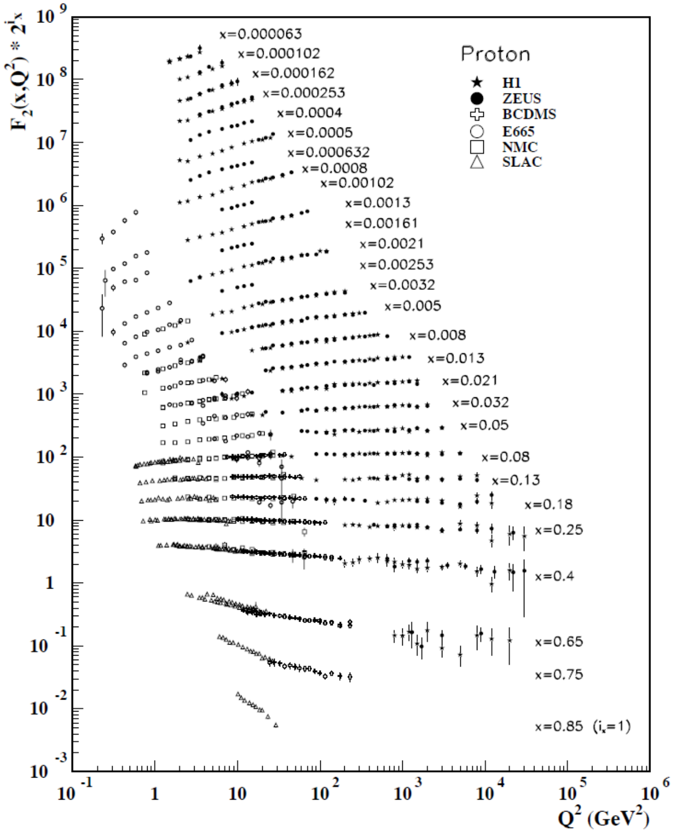


Figure 16.7: The proton structure function F_2^p measured in electromagnetic scattering of positrons on protons (collider experiments ZEUS and H1), in the kinematic domain of the HERA data, for $x > 0.00006$ (*cf.* Fig. 16.10 for data at smaller x and Q^2), and for electrons (SLAC) and muons (BCDMS, E665, NMC) on a fixed target. Statistical and systematic errors added in quadrature are shown. The data are plotted as a function of Q^2 in bins of fixed x. Some points have been slightly offset in Q^2 for clarity. The ZEUS binning in x is used in this plot; all other data are rebinned to the x values of the ZEUS data. For the purpose of plotting, F_2^p has been multiplied by 2^{i_x}, where i_x is the number of the x bin, ranging from $i_x = 1$ ($x = 0.85$) to $i_x = 28$ ($x = 0.000063$). References: **H1**—C. Adloff *et al.*, Eur. Phys. J. **C21**, 33 (2001); C. Adloff *et al.*, Eur. Phys. J. **C30**, 1 (2003); **ZEUS**—S. Chekanov *et al.*, Eur. Phys. J. **C21**, 443 (2001); S. Chekanov *et al.*, Phys. Rev. **D70**, 052001 (2004); **BCDMS**—A.C. Benvenuti *et al.*, Phys. Lett. **B223**, 485 (1989) (as given in [56]) ; **E665**—M.R. Adams *et al.*, Phys. Rev. **D54**, 3006 (1996); **NMC**—M. Arneodo *et al.*, Nucl. Phys. **B483**, 3 (1997); **SLAC**—L.W. Whitlow *et al.*, Phys. Lett. **B282**, 475 (1992).

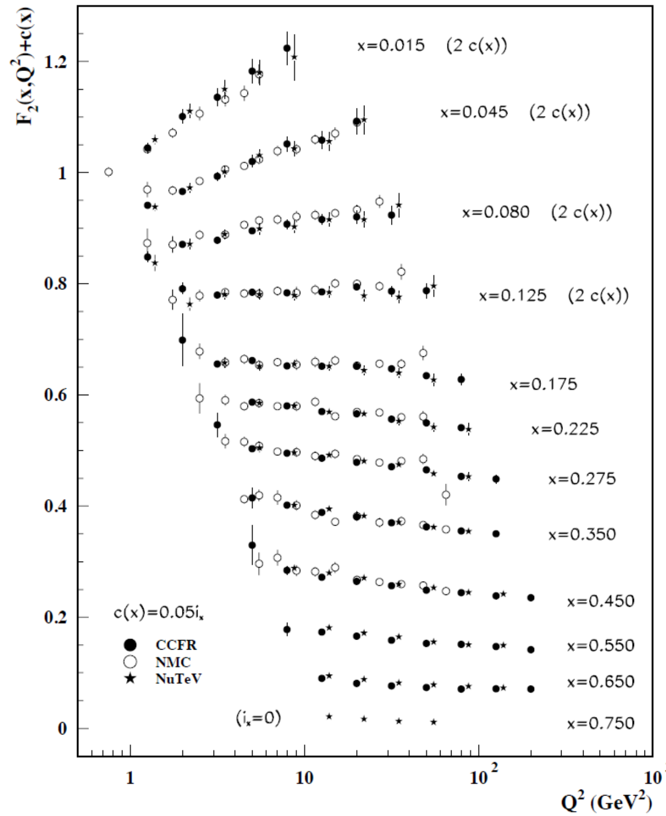


Figure 16.9: The deuteron structure function F_2 measured in deep inelastic scattering of muons on a fixed target (NMC) is compared to the structure function F_2 from neutrino-iron scattering (CCFR and NuTeV) using $F_2^\mu = (5/18)F_2^\nu - x(s + \bar{s})/6$, where heavy-target effects have been taken into account. The data are shown versus Q^2, for bins of fixed x. The NMC data have been rebinned to CCFR and NuTeV x values. Statistical and systematic errors added in quadrature are shown. For the purpose of plotting, a constant $c(x) = 0.05i_x$ is added to F_2, where i_x is the number of the x bin, ranging from 0 ($x = 0.75$) to 7 ($x = 0.175$). For $i_x = 8$ ($x = 0.125$) to 11 ($x = 0.015$), $2c(x)$ has been added. References: **NMC**—M. Arneodo *et al.*, Nucl. Phys. **B483**, 3 (1997); **CCFR/NuTeV**—U.K. Yang *et al.*, Phys. Rev. Lett. **86**, 2741 (2001); **NuTeV**—M. Tzanov *et al.*, Phys. Rev. **D74**, 012008 (2006).

Neutrino mysteries

1. **Neutrinos have mass (we know this from oscillations**
   → come to listen to me tomorrow ☺)

- **Their masses are very tiny**

mass limit of 2.3 eV/c^2 from beta decay

mass limit of <~ 1 eV/c^2 from large scale structure of the Universe

3. **Neutrinos appear in a single helicity (or chirality)?**

But of course weak interaction only couples to left-handed particles and neutrinos have no other known interaction…

So… even if right handed neutrinos existed, they would neither be produced nor be detected!

4. **Why are the neutrino masses so different from those of other quarks and leptons?**
5. **3 families are necessary for CP violation, but why only 3 families?**

……