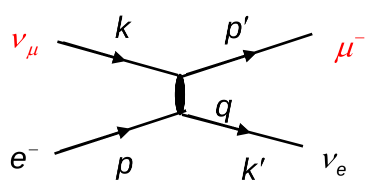
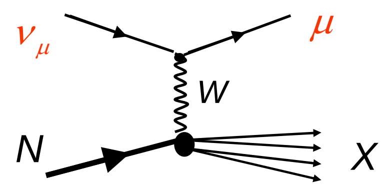
3.7 Neutrino scattering in V-A theory





Very small cross section for νN scattering: $\sigma(\nu N) \approx E_\nu[\text{GeV}]\text{x}10^{-38}\ \text{cm}^2$

$= E_\nu[\text{GeV}]\text{x}10\ \text{fb}$

- intense neutrino beams
- large instrumented targets

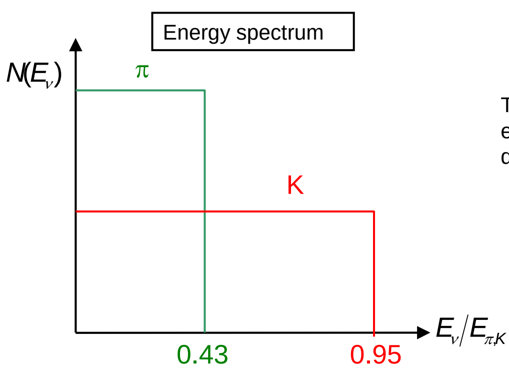
42

Neutrino beams

Sources of neutrino beams are 2-body decays of intense hadron beams

$$\pi^\pm \to \mu^\pm \nu_\mu(\bar{\nu}_\mu) \qquad K^\pm \to \mu^\pm \nu_\mu(\bar{\nu}_\mu)$$

where the pions/kaons are generated in proton-nucleon interactions: p+N$\to\pi$, K



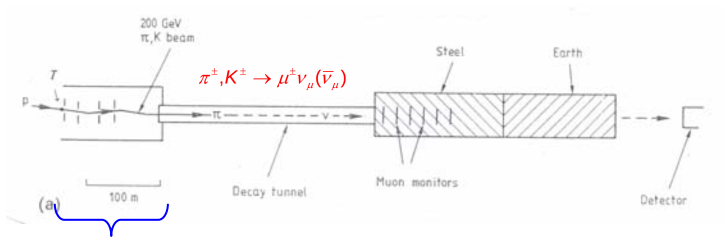
The Lorentz boost transforms the mono-energetic neutrino of the two-body decay into a flat energy spectrum:

$$0 < \frac{E_\nu}{E_{\pi,K}} < 1 - \frac{m_\mu^2}{m_{\pi,K}^2}$$

Beams contain small admixture (0.5%) of electron neutrinos !

43

Generation of neutrino beams

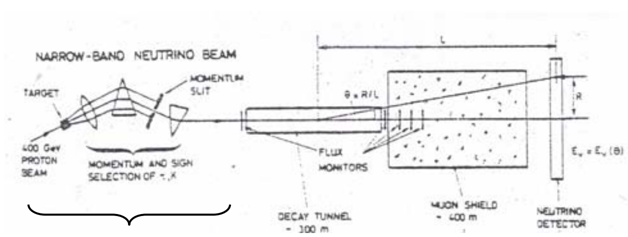


Focusing, momentum & charge selection

1. **~400 GeV proton** beam on a (Be) target: secondary hadrons π, K
2. Momentum and charge selection of π's and K's using a focusing system
3. Selected π's and K's enter a decay tunnel: $\pi^{\pm},K^{\pm} \to \mu^{\pm}\nu_{\mu}(\overline{\nu}_{\mu})$
4. Remaining hadrons and decay muons are filtered by a massive absorber (~400 m iron, concrete, earth): only neutrinos after absorber

There exist 2 different focusing systems for the selection of π's and K's: the two systems lead to neutrino beams with much different energy spectra and fluxes.

Narrow-band neutrino beam:



Deflection and focusing magnets to select and focus hadrons (one charge) of a narrow momentum range

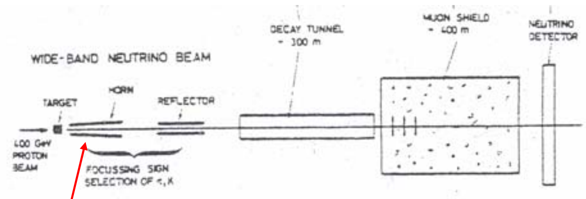
$$\frac{\Delta p_{K,\pi}}{p_{K,\pi}} \approx 7\%$$ (at SPS $p_{K,\pi}$ ~ 200 GeV)

One gets a neutrino beam with a 2-component spectrum

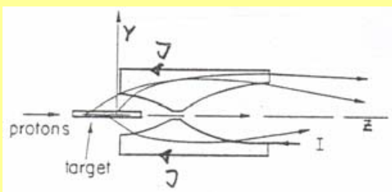
Narrow-band neutrino beam used if one needs to know the exact neutrino flux and wants to achieve max. neutrino energies

45

<u>Wide-band neutrino beam:</u> Magnetic Horn



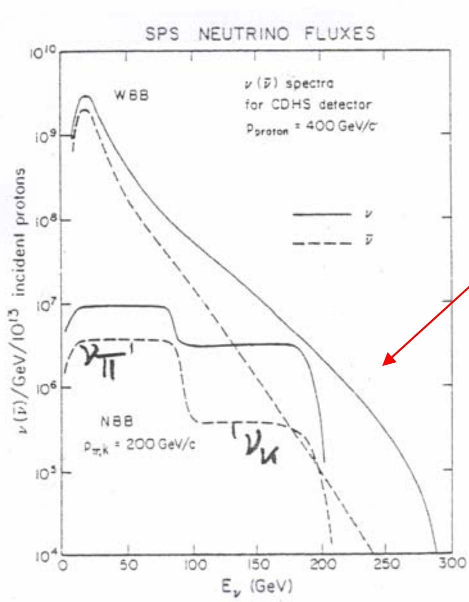
Magnetic Horn (S. van der Meer)



Horn formed from thin aluminum skin

- Short current pulses of 100 to 180 kA
  $\rightarrow$ large short-time magnetic field perpendicular to particle direction

  $\rightarrow$ magnetic deflection similar to a paraboloid for hadrons of one charge
- Advantages: use all $\pi^+/K^+ \rightarrow$ **large ν flux**
- Disadvantage: large background of wrong "sign" ν's



At high energies, there are much more ν than $\bar{\nu}$?

<u>Reason:</u>

•High energy neutrinos are produced from K decays:

$$pN \rightarrow \underset{|uds\rangle}{\Lambda} \quad \underset{|u\bar{s}\rangle}{K^+} \quad \text{with} \quad K^+ \rightarrow \mu^+ \nu_\mu$$

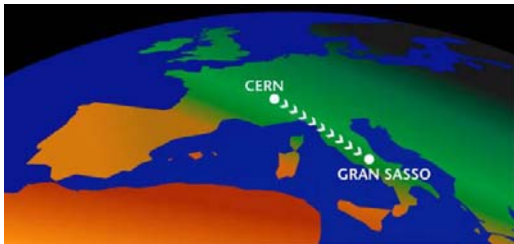
(associated strange baryon production: no anti-baryon production !!)

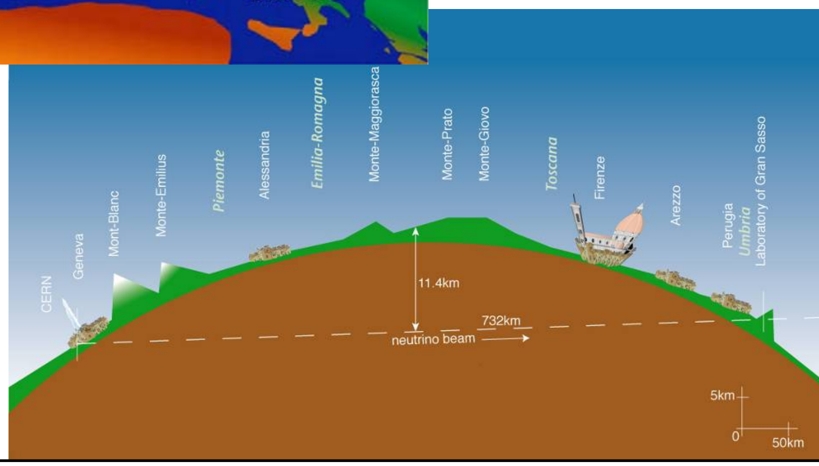
47

CERN Gran Sasso Neutrino Beam (CNGS)

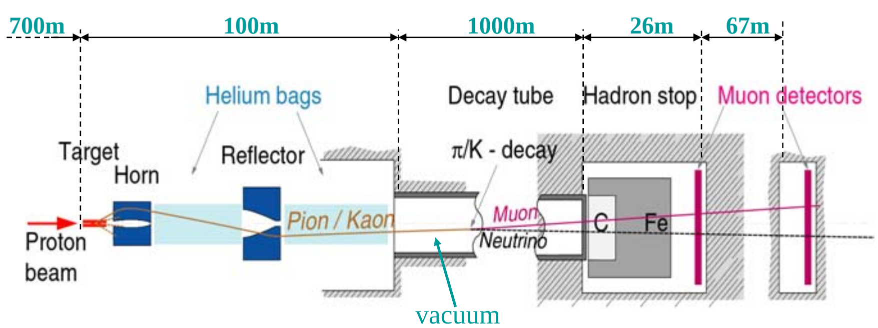
To study neutrino oscillation:

τ appearance for ν_μ beam.





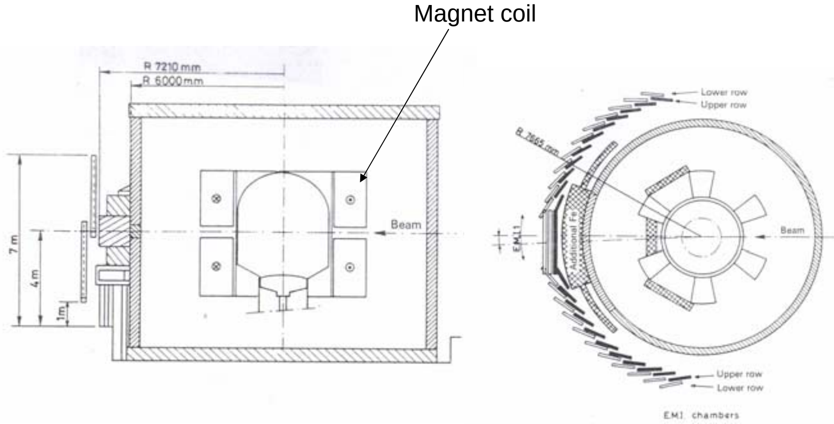
CNGS Layout



$p + C \rightarrow$ (interactions) $\rightarrow \pi^+, K^+ \rightarrow$ (decay in flight) $\rightarrow \mu^+ + \nu_\mu$

49

Neutrino detector: Bubble chamber BEBC (CERN)



3.7 m diameter bubble chamber, filled with lq. hydrogen, deuterium
+ additional muon identifier consisting out of 150 m^2 of MWPC

50

Neutrino event in bubble chamber: BEBC (CERN)

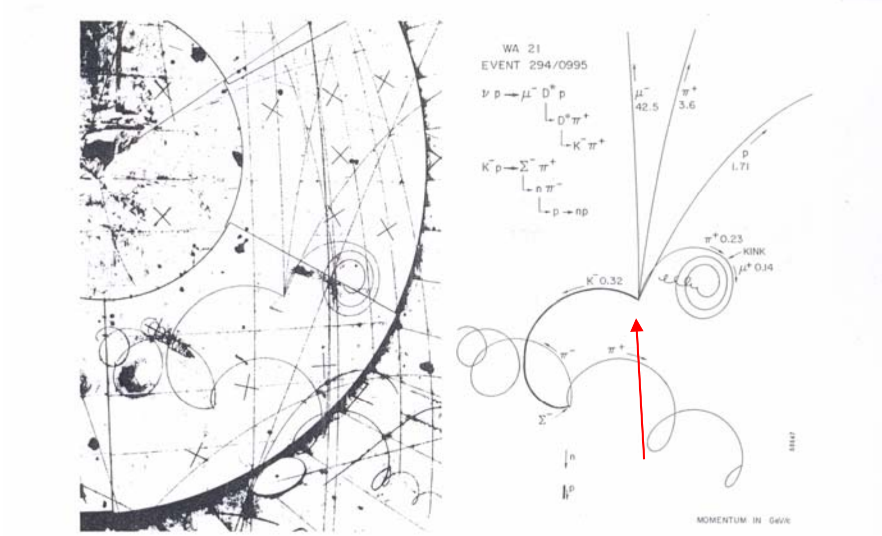
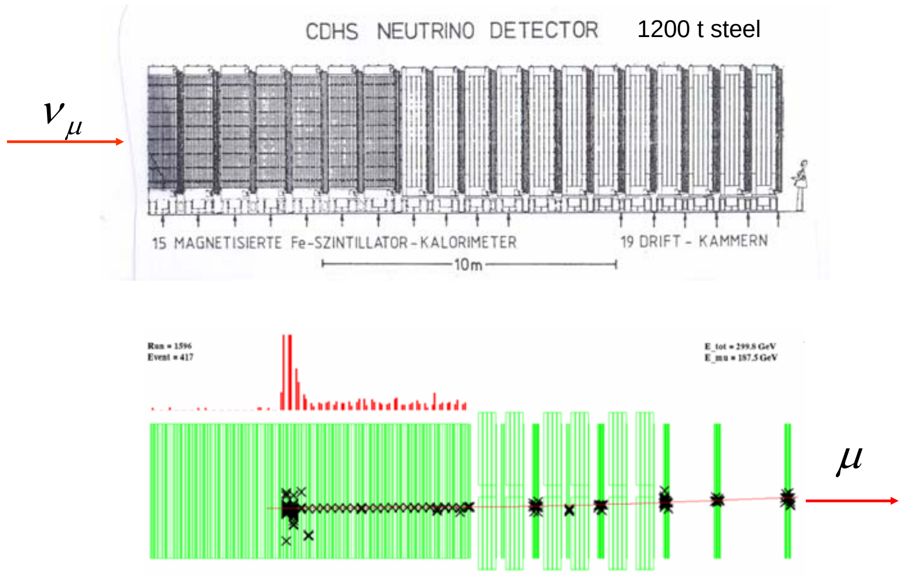
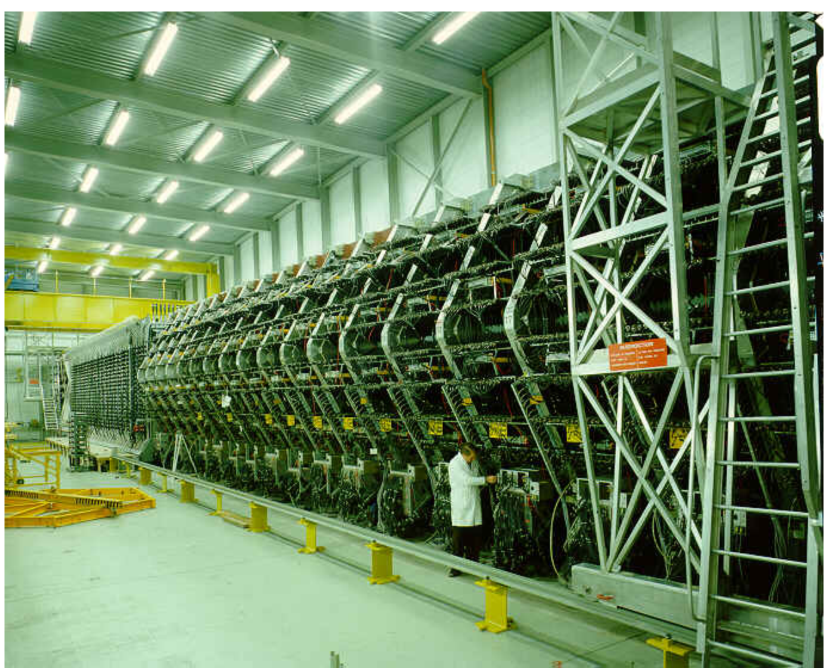


Figure 2.15 Example of charmed-particle production and decay in the hydrogen bubble chamber BEBC exposed to a neutrino beam at the CERN SPS. (Courtesy CERN.)

CHDS (CERN-Dortmund-Heidelberg-Saclay) Experiment

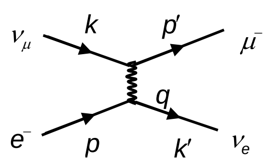


52

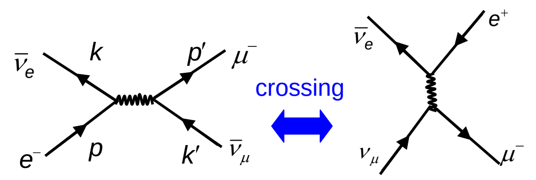


Neutrino-lepton and neutrino-quark reactions

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

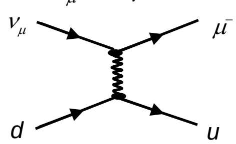


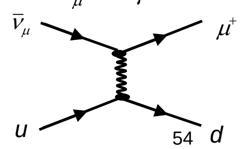
$\overline{\nu}_e e^- \rightarrow \mu^- \overline{\nu}_\mu$ $\qquad$ $\overline{\nu}_e \nu_\mu \rightarrow e^+ \mu^-$



(Anti)neutrino-lepton interaction similar to (Anti)neutrino-quark interaction:
neutrino-lepton results can be applied to deep-inelastic νN scattering.

$\nu_\mu d \rightarrow \mu^- u$ $\qquad$ $\overline{\nu}_\mu u \rightarrow \mu^+ d$



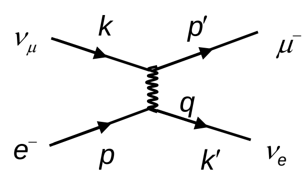


54

a) <u>Neutrino-electron scattering</u>

$$\boxed{\nu_\mu e^- \rightarrow \mu^- \nu_e}$$

ν_e $\qquad$ e^-



$$M = \frac{G_F}{\sqrt{2}}\left[\overline{u}_\nu(k')\gamma_\alpha(1-\gamma^5)u_e(p)\right]\left[\overline{u}_\mu(p')\gamma^\alpha(1-\gamma^5)u_\nu(k)\right]$$

$$\overline{|M|^2} = \frac{1}{2}\sum_{Spins}|M|^2 = \ldots \underset{\uparrow}{=} 64G_F^2(k\cdot p)(k'\cdot p') \underset{\uparrow}{=} 16G_F^2\cdot s^2$$

Limit $m_e \approx m_\mu \approx 0$ $\qquad$ $s=(k+p)^2=2kp=2k'p'$

Using the phase space factor of chapter II:

Although effective 4-fermion theory works well for low q^2 it violates unitarity bound for high q^2!

$$\frac{d\sigma}{d\Omega}(\nu_\mu e^-) = \frac{1}{64\pi^2 s}\overline{|M|^2} = \frac{G_F^2 s}{4\pi^2}$$

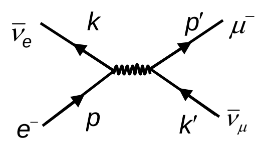
$$\sigma(\nu_\mu e^-) = \frac{G_F^2 s}{\pi} \longleftarrow = 2m_e E_\nu$$

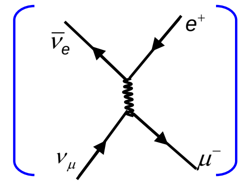
This is a clear indication that the 4-fermion interaction is only an effective low energy approximation – not valid at high energies !!

55

b) Anti-Neutrino-electron scattering (V-A)

$$\boxed{\bar{\nu}_e e^- \rightarrow \bar{\nu}_\mu \mu^-}$$





Crossing: s ⇔ t (u)

$$\overline{|M|^2} = \frac{1}{2}\sum_{Spins}|M|^2 = 16G_F^2 \cdot t^2 = 4G_F^2 \cdot s^2(1-\cos\theta)^2$$

$$\boxed{\begin{aligned} \frac{d\sigma}{d\Omega}(\bar{\nu}e^-) &= \frac{G_F^2 s}{16\pi^2}(1-\cos\theta)^2 \\ \sigma(\bar{\nu}e^-) &= \frac{G_F^2 s}{3\pi} \end{aligned}}$$

56

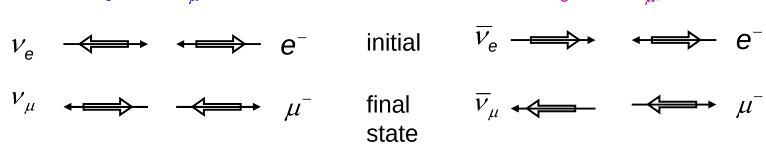
Result of V-A structure

For the charged current (CC) contribution to the (anti) neutrino electron scattering one finds $\frac{\sigma_{\nu e}^{cc}}{\sigma_{\bar{\nu} e}^{cc}} = 3$

Different angular distribution of (anti) neutrino scattering can be understood from a helicity discussion

$$\begin{cases} \frac{d\sigma}{d\Omega}(\nu_e e^- \rightarrow \nu_\mu \mu^-) = \frac{G_F^2 s}{4\pi^2} \\ \frac{d\sigma}{d\Omega}(\bar{\nu}_e e^- \rightarrow \bar{\nu}_\mu \mu^-) = \frac{G_F^2 s}{16\pi^2}(1-\cos\theta)^2 \end{cases}$$

$\nu_e e^- \rightarrow \nu_\mu \mu^-$ $\qquad$ $\bar{\nu}_e e^- \rightarrow \bar{\nu}_\mu \mu^-$



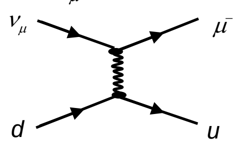
Allowed → isotropic

Forbidden (angular mom.) → (1-cosθ) suppression

57

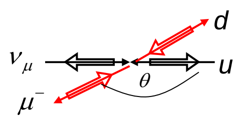
c) (Anti) neutrino-quark scattering

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



$$\frac{d\sigma}{d\Omega}(\nu_\mu d) = \frac{G_F^2 s}{4\pi^2}$$

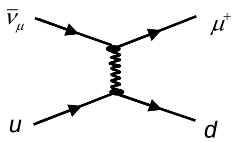
$$\sigma(\nu_\mu d) = \frac{G_F^2 s}{\pi}$$



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

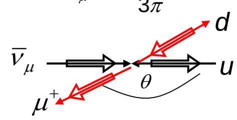
$$\frac{d\sigma}{d\Omega}(\bar{\nu}_\mu \bar{d}) = \frac{d\sigma}{d\Omega}(\nu_\mu d)$$

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



$$\frac{d\sigma}{d\Omega}(\bar{\nu}_\mu u) = \frac{G_F^2 s}{16\pi^2}(1+\cos\theta)^2$$

$$\sigma(\bar{\nu}_\mu u) = \frac{G_F^2 s}{3\pi}$$



$\nu_\mu \bar{u} \to \mu^- \bar{d}$

$$\frac{d\sigma}{d\Omega}(\nu_\mu \bar{u}) = \frac{d\sigma}{d\Omega}(\bar{\nu}_\mu u)$$

Neutrinos only interact w/ d and anti-u quarks
Anti-neutrinos only interact w/ u and anti-d quarks

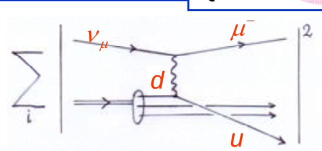
58

d) Neutrino-nucleon (iso-scalar) scattering

Not treated in this lecture

QPM: $x = \frac{Q^2}{2M\nu}$ $y = \frac{\nu}{E}$ $\nu = E - E'$

$$\frac{d\sigma(\nu_\mu N \to \mu^- X)}{dy} =$$



$$\frac{d^2\sigma(\nu N)}{dxdy} = \sum_i f_i(x) \left(\frac{d\sigma_i(\nu q_i)}{dy} \right)_{\hat{s}=xs}$$

$$\frac{d^2\sigma(\nu N)}{dxdy} = \frac{G_F^2 xs}{2\pi} \cdot \left[Q(x) + \bar{Q}(x)(1-y)^2 \right]$$

$$\frac{d\sigma(\nu d)}{dy} = \frac{G_F^2 xs}{\pi}$$

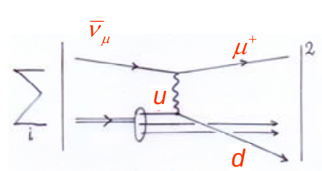
$$\frac{d\sigma(\nu \bar{u})}{dy} = \frac{G_F^2 xs}{\pi}(1-y)^2$$

Unter Vernachlässigung der Massen gilt:

$$y = \frac{1-\cos\theta}{2}$$

$$1 - y \approx \frac{1}{2}(1+\cos\theta)$$

$$\frac{d\sigma(\bar{\nu}_\mu N \to \mu^+ X)}{dy} =$$



$$\frac{d^2\sigma(\bar{\nu} N)}{dxdy} = \frac{G_F^2 xs}{2\pi} \cdot \left[\bar{Q}(x) + Q(x)(1-y)^2 \right]$$

59

Total cross section after integration over x and y (0…1):

$$\sigma(\nu N) = \frac{G_F^2 M E_\nu}{2\pi} \cdot \left[Q_l + \frac{1}{3}\overline{Q}_l \right]$$

$$\sigma(\overline{\nu} N) = \frac{G_F^2 M E_\nu}{2\pi} \cdot \left[\overline{Q}_l + \frac{1}{3} Q_l \right]$$

with $Q_l = \int xQ(x)dx$

$$\boxed{R = \frac{\sigma_{\overline{\nu}N}}{\sigma_{\nu N}} = \frac{1+3\overline{Q}_l/Q_l}{3+\overline{Q}_l/Q_l}}$$

If nucleon consists only of valence quarks ($\overline{Q}$=0): R=1/3 , because of V-A structure

Measurement: $R = \frac{0.34}{0.67} \Rightarrow \overline{Q}_l/Q_l \approx 0.15$

$\Rightarrow$ There are sea quarks !

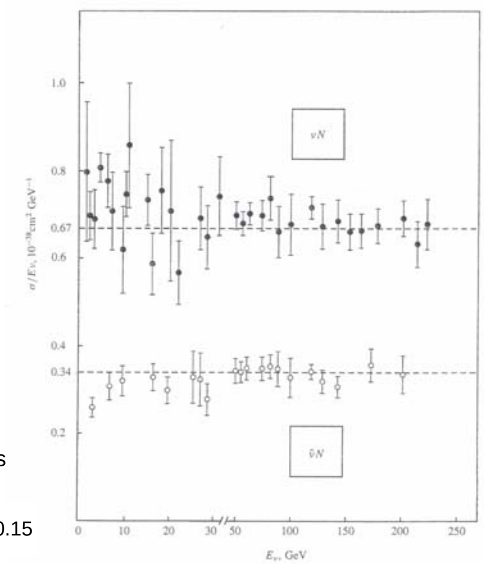


Fig. 5.13. Neutrino and antineutrino cross-sections on nucleons. The ratio σ/E_ν is plotted as a function of energy and is indeed a constant, as predicted in (5.45) and (5.46).

3.8 Problems with pure V-A theory

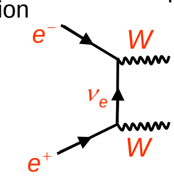
- Cross section for $\nu e^- \to e^- \nu_e$ in 4-fermion ansatz: i.e. cross section goes to infinity if s→∞: violates unitarity
  $$\sigma(\nu e^-) = \frac{G_F^2 s}{\pi}$$
- Lee and Wu (1965) introduced a massive exchange boson. Effect of propagator:

$$\frac{G_F}{\sqrt{2}} \mapsto \frac{G_F}{\sqrt{2}} \frac{1}{1-q^2/M_W^2} \qquad \sigma(\nu e^-) \mapsto const.$$

Not trivial, see e.g.: C.Quigg, Gauge Theory of Strong and Weak interaction

This fix leads to a new problem, namely the violation of unitarity of the predicted W pair production !

W pair production:



Violates unitarity

We need a new theory: Standard Model

61

4. Neutral currents (CERN, 1973)

Gargamelle Bubble Chamber

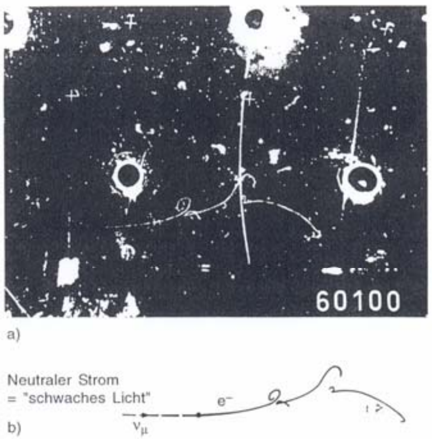
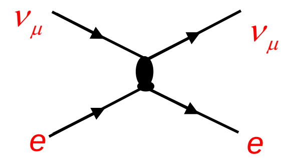


Abb. 9. Dieses erste Ereignis mit einem neutralen schwachen Strom wurde in Aachen entdeckt. Ein Neutrino dringt von links in die Blasenkammer ein (auf dem Bild nicht sichtbar) und wird elastisch an einem Elektron gestreut. Das Elektron ist als rechte Spurkaskade (Bremsstrahlung) zu erkennen. Dieses Bild ist in die Geschichte des CERN eingegangen

One out of three $\nu e \to \nu e$ events

$$\nu_\mu + e^- \to \nu_\mu + e^-$$



Neutral current νN events appear with a significant rate:

$$R_\nu = \frac{\sigma_{NC}(\nu N \to \nu X)}{\sigma_{CC}(\nu N \to \mu X)} = 0.307 \pm 0.008$$

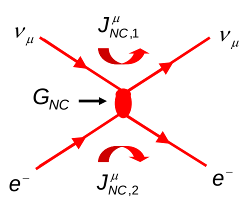
i.e. approx. 1/3 of the νN interactions are neutral current interactions.

62

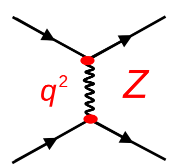
Structure of Neutral currents

Ansatz: four-fermion interaction

as $q^2 \to 0$ approximation of:



$$M = \frac{8G_{NC}}{\sqrt{2}} \cdot J_{NC,1,\mu} \cdot J^\mu_{NC,2}$$



Experimental determination of the structure of the weak neutral currents:

$$J^\mu_{NC} = \bar{u}\,\gamma^\mu \frac{1}{2}(g_V - g_A\gamma^5)u$$

➡ Neutral weak interaction couples to left- and right-handed chiral fermion currents differently:

$$g_L = \frac{1}{2}(g_V + g_A) \qquad g_R = \frac{1}{2}(g_V - g_A)$$

$$J^\mu_{NC} = \bar{u}\gamma^\mu\left(g_R\frac{1+\gamma^5}{2} + g_L\frac{1-\gamma^5}{2}\right)u$$

63

4.1 Vector and axial-vector couplings

Standard Model prediction for g_v and g_A:

	g_V	g_A
ν	$1/2$	$1/2$
ℓ^-	$-1/2 + 2\sin^2\theta_W$	$-1/2$
$u-quark$	$+1/2 - 4/3\sin^2\theta_W$	$1/2$
$d-quark$	$-1/2 + 2/3\sin^2\theta_W$	$-1/2$

with $\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} \approx 0.223$

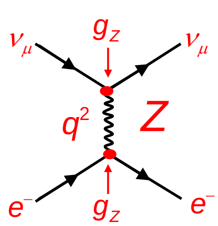
In case of the left-handed neutrinos: $$J_\nu^\mu = \bar{u}_\nu \gamma^\mu \frac{1}{2}\cdot\frac{1}{2}\underbrace{(1-\gamma^5)}_{\text{pure V-A structure}} u_\nu$$

(consistent, only LH neutrinos)

64

4.2 Effective coupling G_{NC}

(copy of charged current)



$$J_e^\mu = \bar{u}\,\gamma^\mu \frac{1}{2}(g_V - g_A\gamma^5)u$$

$$M = J_{e,\mu}\cdot g_Z \cdot \frac{g_{\mu\nu} - q_\mu q_\nu / M_Z^2}{q^2 - M_Z^2}\cdot g_Z \cdot J_\nu^\nu$$

As 4-fermion interaction is the $q^2 \to 0$ approximation of a massive boson exchange:

$$M = \frac{8G_{NC}}{\sqrt{2}}\cdot J_{e,\mu}\cdot J_\nu^\mu$$

Comparison of the coupling constants in the $q^2 \to 0$ limit:

$$\frac{G_{NC}}{\sqrt{2}} = \frac{g_Z^2}{8M_Z^2} = \frac{g_W^2}{8M_W^2}\cdot\underbrace{\frac{g_Z^2 M_W^2}{g_W^2 M_Z^2}}_{\rho=1 \text{ in the SM}} = \frac{g_W^2}{8M_W^2}\cdot\rho = \frac{G_F}{\sqrt{2}}$$

65