# Electroweak interactions

3224
Nuclear and Particle Physics
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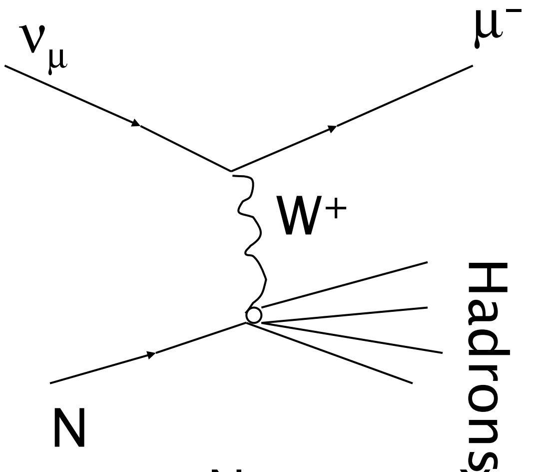
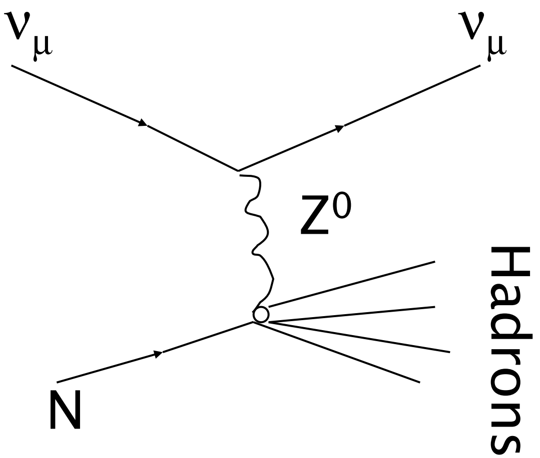
# Charged and Neutral currents



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

**Charged currents**



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

**Neutral currents**

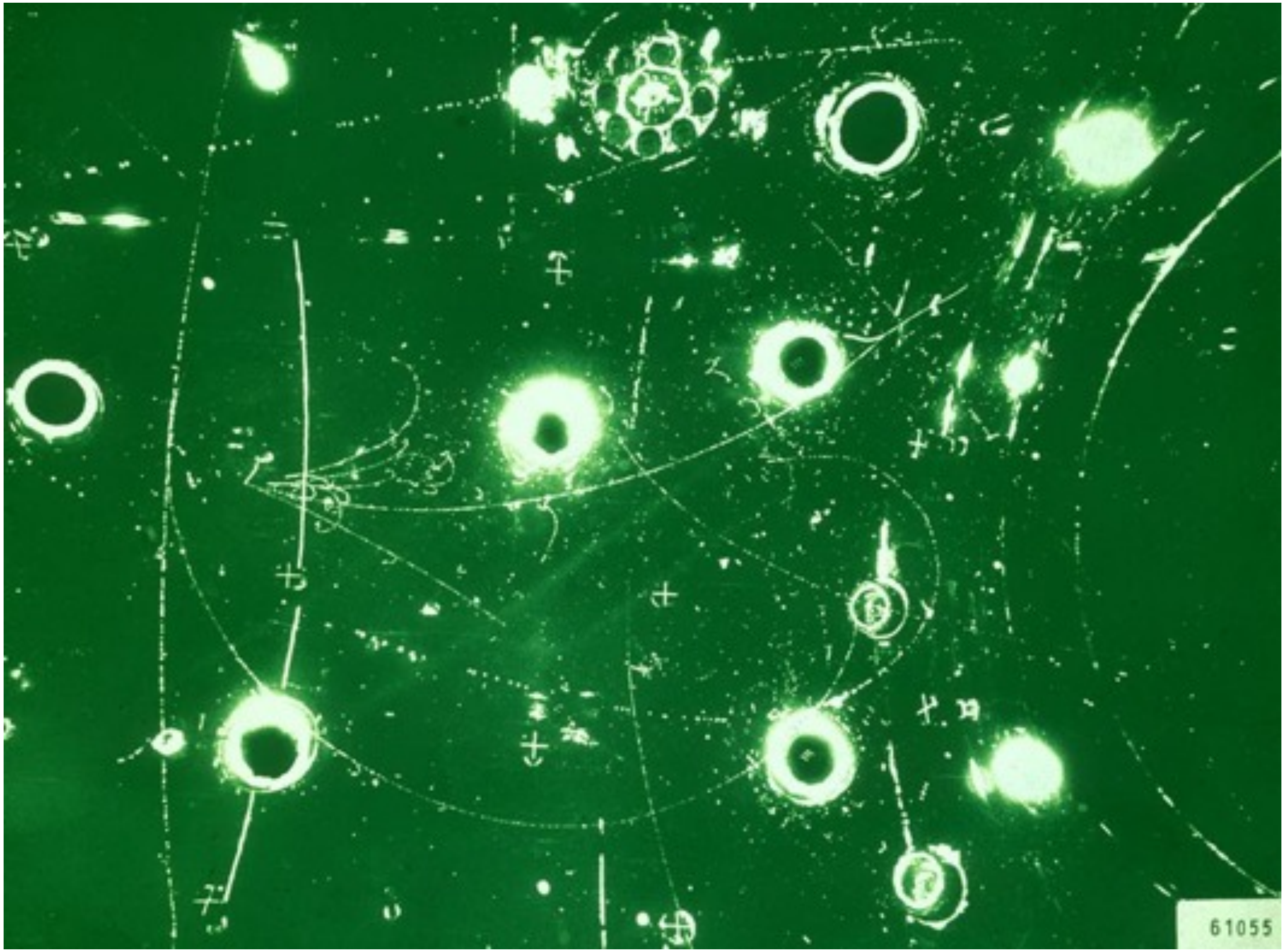
Neutral currents were predicted by electroweak theory

Experimentally observed only in 1973

Both W, Z - spin-1 bosons (force carriers of weak interaction)

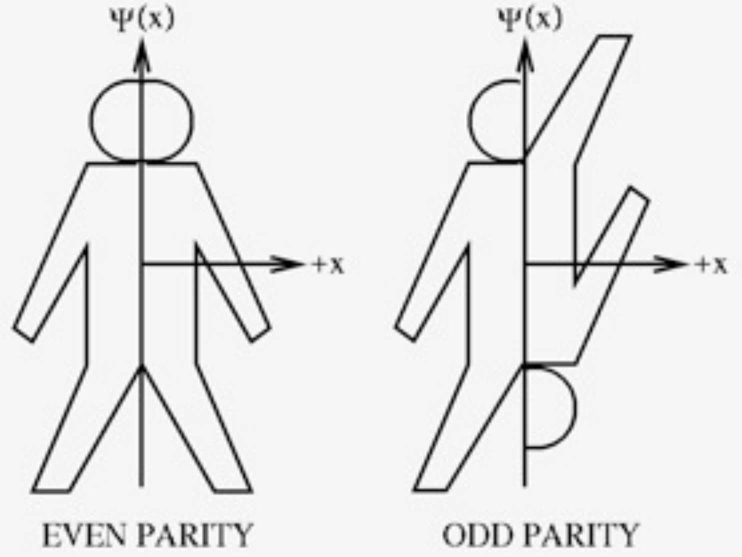
The unification of weak and EM interactions becomes

# The first neutral current event (1973)



# Symmetries of the weak interaction

Parity (P)

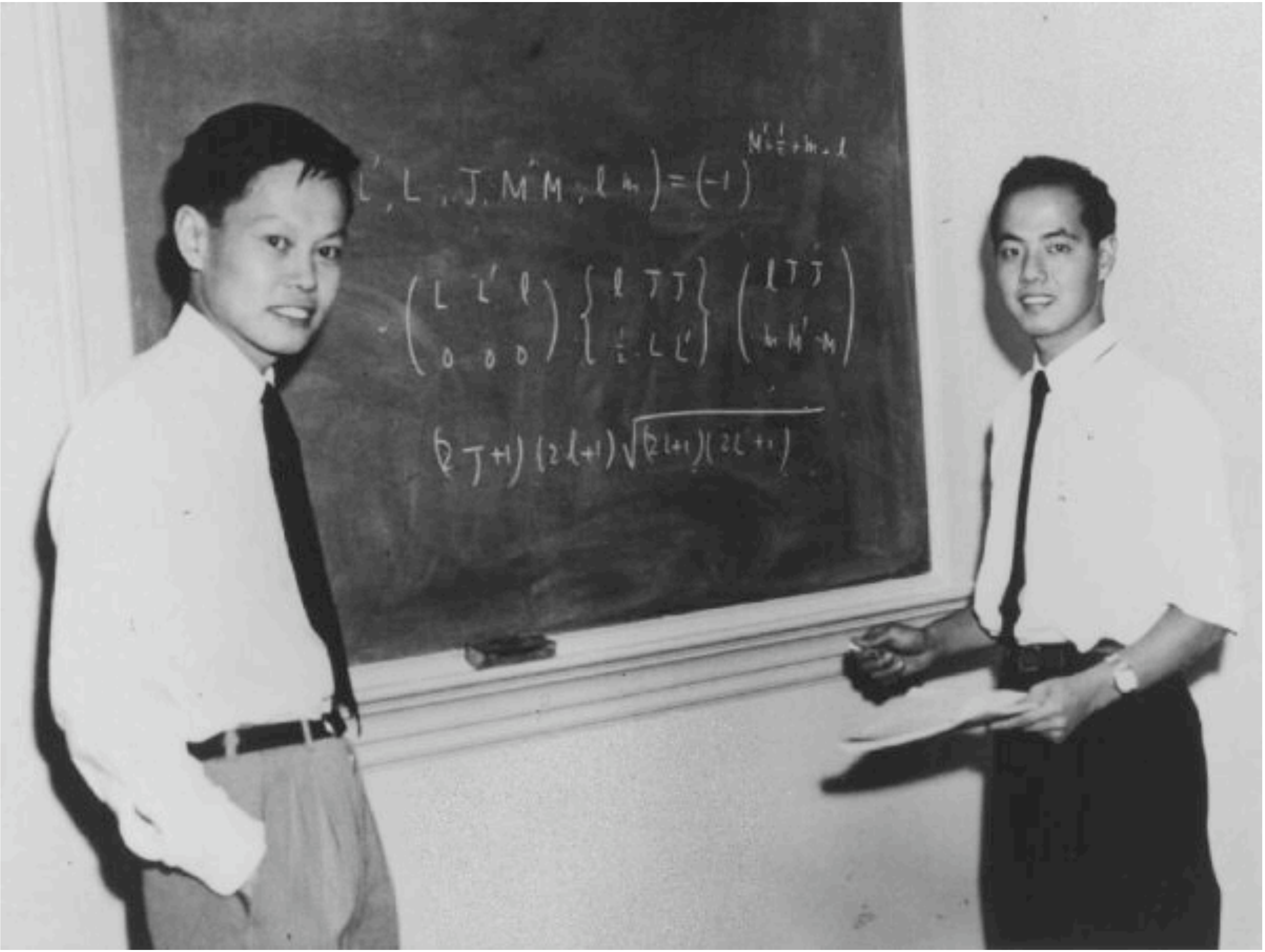


Charge conjugation (C)

$e^- \Rightarrow e^+$

$\pi^+ \Rightarrow \pi^-$

For a long time parity conservation
believed to be a universal law of nature
Lee and Yang suggested (1956) that there was no evidence for
parity conservation in weak interactions.


L', L ; J, M'M ; l m ) = (-1)
N+1/2+m-l
L L' l / 0 0 0
l J J / 1/2 L L'
l J J / m M' -m
(2J+1) (2l+1) √(2l+1)(2L+1)

# Experimental evidence for parity violation
# β-decay of polarised $^{60}$Co
# (Wu *etc*, 1957)

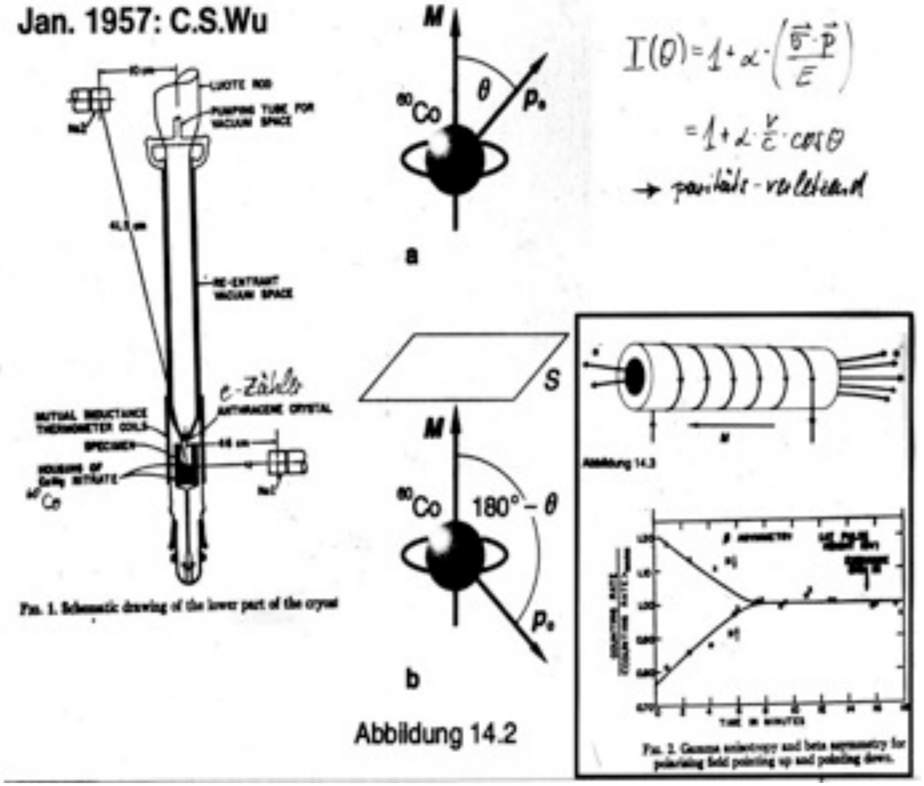

Jan. 1957: C.S.Wu

FIG. 1. Schematic drawing of the lower part of the cryost

$$I(\theta) = 1 + \alpha \cdot \left( \frac{\vec{\sigma} \cdot \vec{p}}{E} \right)$$

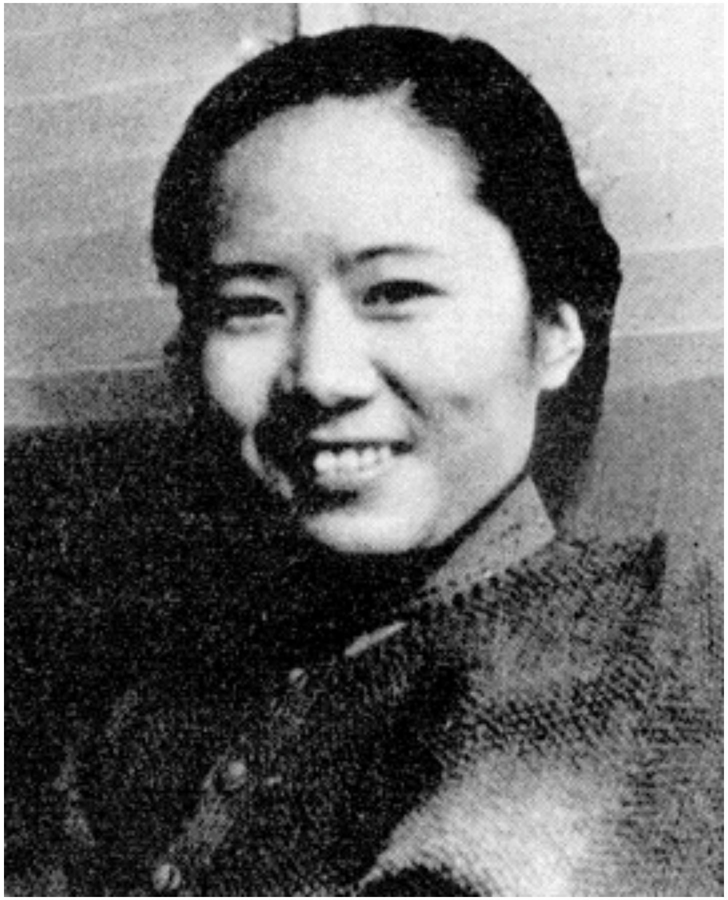
$$= 1 + \alpha \cdot \frac{v}{c} \cdot \cos\theta$$

→ paritäts-verletzend

Abbildung 14.2

Abbildung 14.3

FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.



# Experimental evidence for parity violation
# $\beta$-decay of polarised $^{60}$Co
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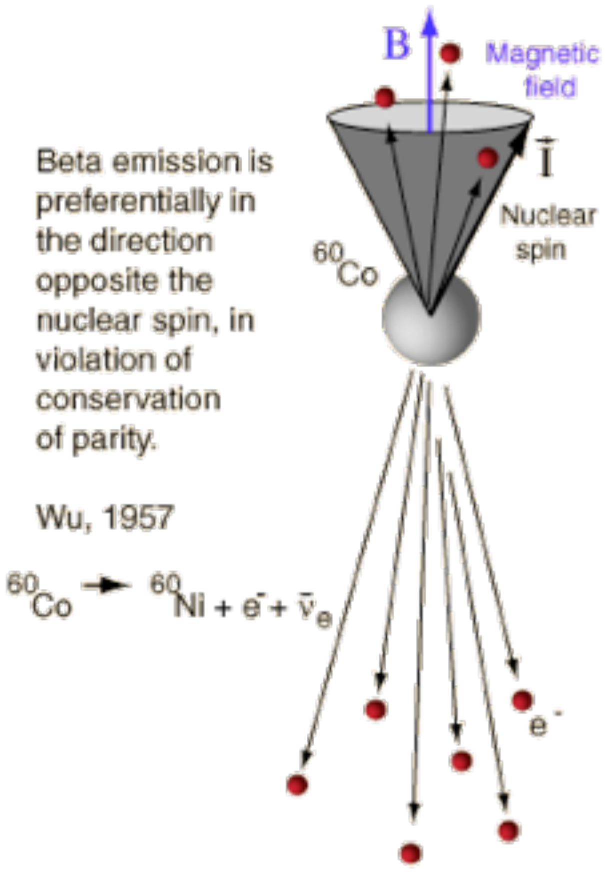


Beta emission is preferentially in the direction opposite the nuclear spin, in violation of conservation of parity.

Wu, 1957

$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e$

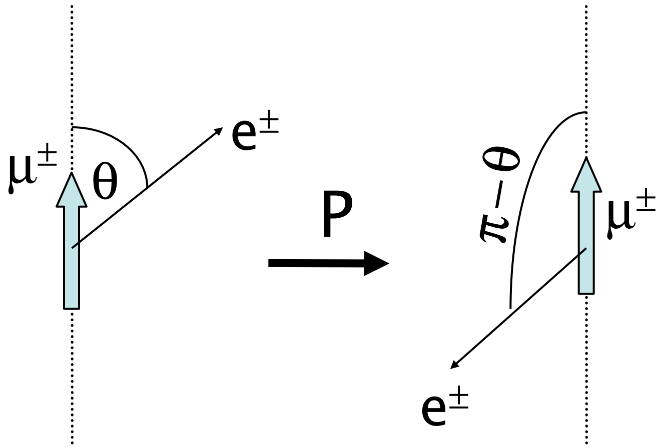
- $^{60}$Co was placed inside a solenoid and cooled to 0.01K to align nuclear spin parallel to the field direction
- Parity violation is established by the observation a forward–backward decay asymmetry
- A shocking event and

# Symmetries of the weak interactions

- Charge conjugation, C, is also not conserved in weak interactions
- C- and P-violation effects have their origin in the spin dependence of weak interactions
- C- and P-violation are large effects, BUT the combination of the two, CP-invariance, is almost exactly conserved
- Tiny CP-violation is enormously important. First hints in K’s decays (see later). Now and in future focus on CP-violation studies in other hadrons and neutrino sector

# C- and P- violation in muon decay

Angular distribution of electrons and positrons in the decays of polarized muons



$$\Gamma_{\mu\pm}(\cos\theta)=\frac{1}{2}\Gamma_\pm\left(1-\frac{\xi_\pm}{3}\cos\theta\right)$$

asymmetry term

- C- transforms $\mu^-$ decay to $\mu^+$ decay
- C-invariance implies that $\Gamma_+=\Gamma_-$, and $\xi_+=\xi_-$
- P- preserves the particle id but reverses their momenta while leaving their spins unchanged:

$$\Gamma_{\mu\pm}(\cos\theta)=\Gamma_{\mu\pm}(-\cos\theta)$$

Hence $\xi_\pm=0$

- Experiment: Lifetimes the same, BUT: $\xi_-=-\xi_+=1.00\pm0.04$

# CP-invariance

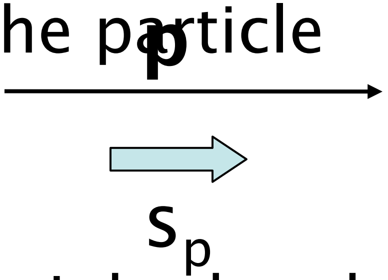
- Why do the $\mu^+$ and $\mu^-$ have the same lifetime if C-invariance is violated? ⇒ **CP-conservation**
- CP- operator applied to muon decay changes $\theta$ to $\pi-\theta$ and particle to antiparticle, i.e. CP-invariance implies

$$\Gamma_{\mu+}(\cos\theta)=\Gamma_{\mu-}(-\cos\theta)$$

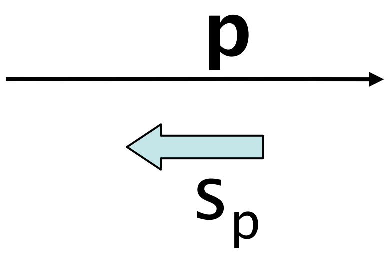
- Hence $\Gamma_+=\Gamma_-$ and $\xi_+=-\xi_-$ which is exactly what is observed!
- Tiny deviations from CP-invariance are very important!

# Spin structure of the weak interactions
# Neutrinos

Helicity states: spin is quantized along the direction of motion of the particle



right-handed

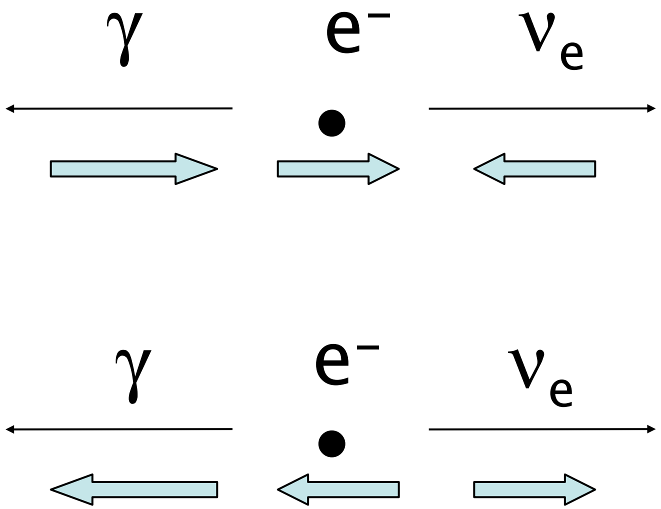


left-handed

$$\begin{tikzcd}
\boxed{\nu_L} \arrow[r, "P"] \arrow[d, "C"'] \arrow[dr, "CP"] & \nu_R \\
\bar{\nu}_L & \boxed{\bar{\nu}_R}
\end{tikzcd}$$

Only left-handed neutrinos $\nu_L$ and right-handed antineutrinos $\bar{\nu}_R$ are observed in nature !

# Goldhaber experiment (1958) to measure neutrino's helicity



$$e^- + {}^{152}\mathrm{Eu}(J=0) \rightarrow {}^{152}\mathrm{Sm}^*(J=1) + \nu$$

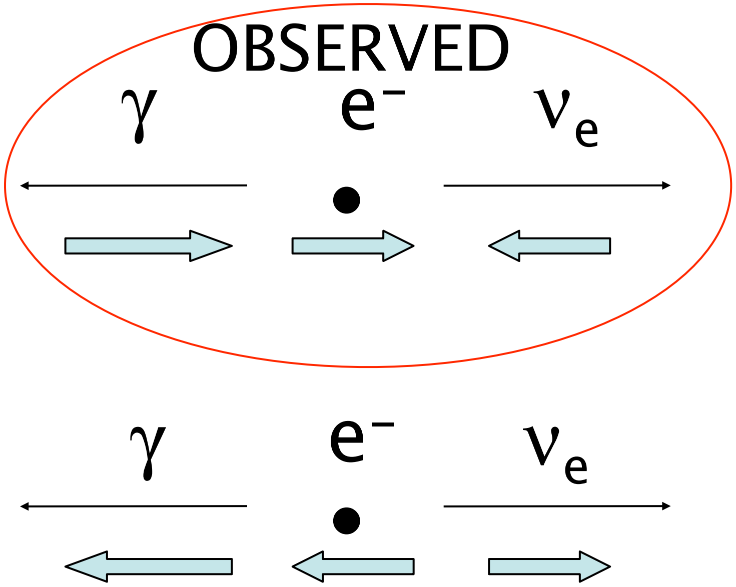
$$ {}^{152}\mathrm{Sm}^*(J=1) \rightarrow {}^{152}\mathrm{Sm}(J=0) + \gamma$$

- The helicity of $\nu_e$ was deduced from the measured helicity of the photon by applying angular momentum conservation
- The polarization of the photons was determined from their absorption in magnetized iron

$\nu$

- Only left-handed ν's observed

# Goldhaber experiment (1958) to measure neutrino’s helicity



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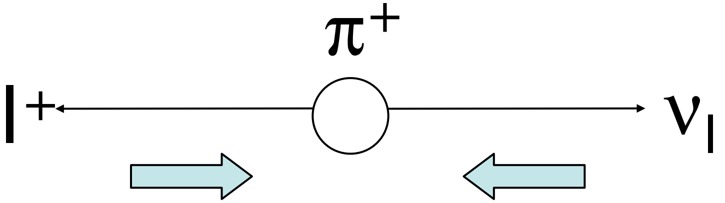
$\nu$

- Only left-handed $\nu$’s observed

# V-A interaction

- The spin dependence of weak interactions is represented by V–A interaction.
- V denotes a proper vector (momentum, **p**)
- A – is an axial vector, whose direction is unchanged by parity transformation (angular momentum $\mathbf{L} = \mathbf{r} \times \mathbf{p}$)
- Only V–A observed in weak interactions
- Because $\nu$'s have very small (in SM zero) mass they are always left-handed.
- For other particles it is true in ultra-relativistic limits. In this case the contribution of the “forbidden” helicity states ($e^-_R$, $e^+_L$) are suppressed by factors

# Pion decay and spin structure



- If l = $\mu$, muon is non-relativistic $\Rightarrow$ both helicity states are allowed
- If l = e, positron is relativistic $\Rightarrow$ this mode is suppressed by $\sim 2(m_e/m_\pi)^2 = 2.6\times10^{-5}$

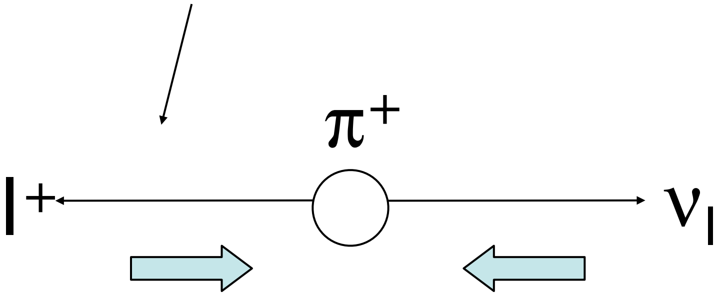
$\pi^+ \to l^+ + \nu_l$ l = e, $\mu$

Experiment: $\frac{\Gamma(\pi^+ \to e^+\nu_e)}{\Gamma(\pi^+ \to \mu^+\nu_\mu)} = (1.218 \pm 0.014)\times10^{-4}$

which is in excellent agreement with calculation if difference in phase space is taken into account

# Pion decay and spin structure

muons are always emitted polarized!



$\pi^+ \to l^+ + \nu_l$ $\qquad$ $l = e, \mu$

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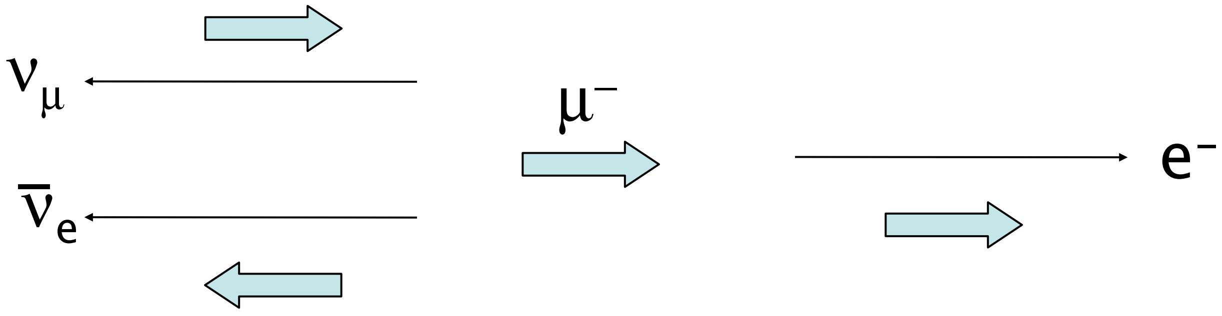
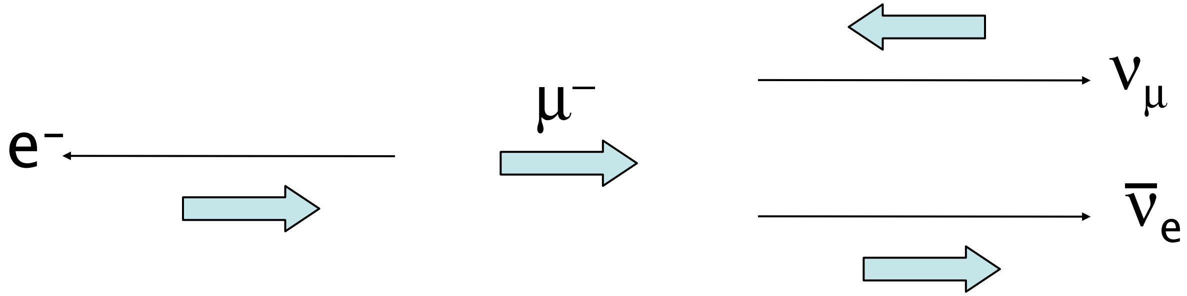
# Muon decay and spin structure



“Forbidden”

Highest energy e⁻ a
emitted in the direc
opposite to $\nu_\mu$ and

$$E_{e_{\max}} = \frac{m_\mu}{2}\left(1+\frac{m_e^2}{m_\mu^2}\right) >> m_e$$



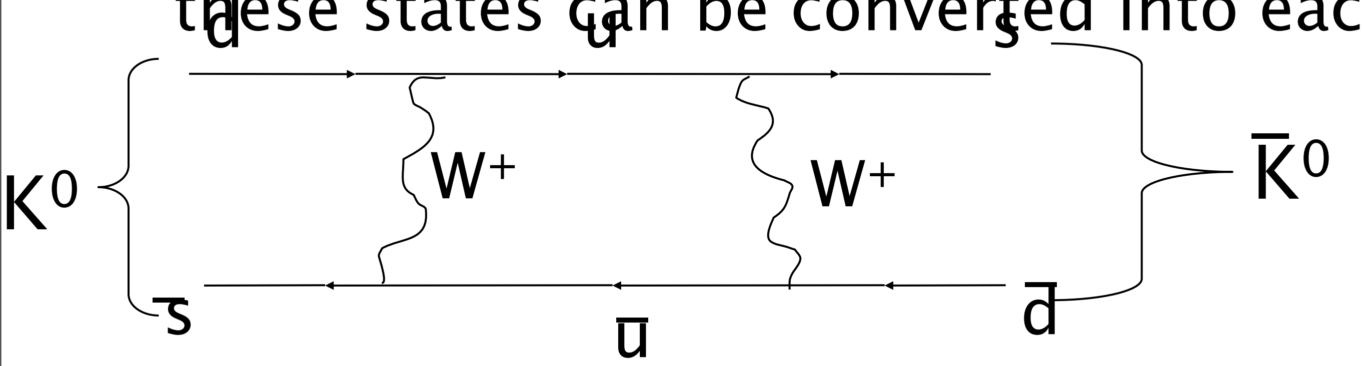
“Allowed”

Explains forward-backward
asymmetry

# $K^0 - \bar{K}^0$ mixing

$$K^0 = d\bar{s}\ (S = +1) \quad \bar{K}^0 = s\bar{d}\ (S = -1)$$

However, because S is not conserved in weak interactions
these states can be converted into each other, e.g.



It is not possible for quantum numbers which are conserved in all
interactions. For example p and $\bar{p}$ can not mix since baryon number
must be conserved

Thus, the observed physical particles correspond not to

# $K^0 - \bar{K}^0$ mixing

First, assume that CP is conserved exactly:

$$C\psi_{K^0}(\vec{p}) = -\psi_{\bar{K}^0}(\vec{p}), \qquad C\psi_{\bar{K}^0}(\vec{p}) = -\psi_{K^0}(\vec{p})$$

$$P\psi_{K^0}(\vec{p}=\vec{0}) = -\psi_{K^0}(\vec{p}=\vec{0}), \qquad P\psi_{\bar{K}^0}(\vec{p}=\vec{0}) = -\psi_{\bar{K}^0}(\vec{p}=\vec{0})$$

Then

$$CP\psi_{K^0}(\vec{p}=\vec{0}) = \psi_{\bar{K}^0}(\vec{p}=\vec{0}), \qquad CP\psi_{\bar{K}^0}(\vec{p}=\vec{0}) = \psi_{K^0}(\vec{p}=\vec{0})$$

From here we can derive

$$\psi_{K_1^0}(\vec{p}=\vec{0}) = \frac{1}{\sqrt{2}}\left\{\psi_{K^0}(\vec{p}=\vec{0}) + \psi_{\bar{K}^0}(\vec{p}=\vec{0})\right\}$$

$$\psi_{K_2^0}(\vec{p}=\vec{0}) = \frac{1}{\sqrt{2}}\left\{\psi_{K^0}(\vec{p}=\vec{0}) - \psi_{\bar{K}^0}(\vec{p}=\vec{0})\right\}$$

with

$$CP\psi_{K_1^0}(\vec{p}=\vec{0}) = \psi_{K_1^0}(\vec{p}=\vec{0}), \qquad CP\psi_{K_2^0}(\vec{p}=\vec{0}) = -\psi_{K_2^0}(\vec{p}=\vec{0})$$

# $K^0 - \bar{K}^0$ mixing

If CP is conserved

- $K_1^0$ should decay entirely to states with CP = 1
- $K_2^0$ should decay entirely to states with CP = -1

We will see now that 2π final states of K-decay have CP=+1
while 3π final state have CP = -1.
Hence

$K_1^0 \circledR \pi^+\pi^-,\pi^0\pi^0$ and $K_2^0 \circledR \pi^+\pi^-\pi^0,\pi^0\pi^0\pi^0$ allowed by CP-conservation

$K_1^0 \circledR \pi^+\pi^-\pi^0,\pi^0\pi^0\pi^0$ and $K_2^0 \circledR \pi^+\pi^-,\pi^0\pi^0$ forbidden by CP-conservation

# K→2π

Consider $K^0$ ® $\pi^0\pi^0$

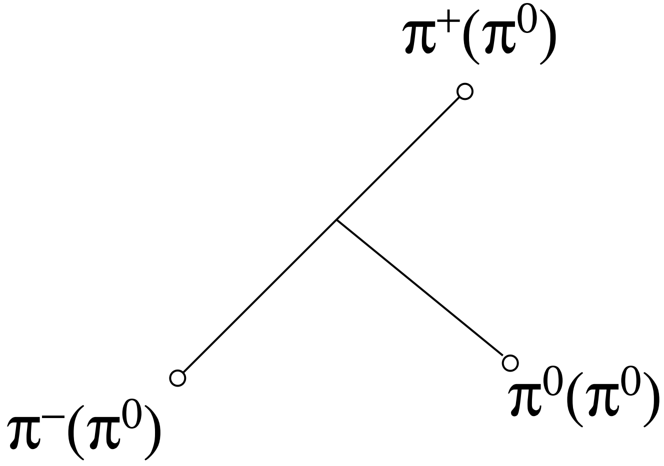
Since K has spin-0, the pion pair must have zero orbital angular momentum in the rest frame of the decaying particle. Therefore its parity is

$P = P_\pi^2(-1)^L = 1$ where $P_\pi = -1$ is the intrinsic parity of pion

The C-parity is $C = (C_{\pi^0})^2 = 1$ where $C_{\pi^0} = 1$ is the parity of $\pi^0$

Hence CP = +1 (the same is for $K^0 \rightarrow \pi^+\pi^-$)

# K→3π



$\vec{L} = \vec{L}_{12} + \vec{L}_3 = \vec{0}$ since the decaying particle has spin-0

This means $L_{12} = L_3$ and

$P = P_\pi^3 (-1)^{L_{12}} (-1)^{L_3} = -1$ for $\pi^0\pi^0\pi^0$ final state and $C = (C_{\pi^0})^3 = 1$

Hence CP = −1 (the same for $\pi^+\pi^-\pi^0$)

# K-long and K-short

Experimentally, two neutral kaons were observed:
short, $K_S^0$ ($\tau = 0.89\times10^{-10}$ s),
and long-lived, $K_L^0$ ($\tau = 0.52\times10^{-7}$ s)

The major pion decay modes were:
$K_S^0 \to 2\pi$ and $K_L^0 \to 3\pi$

So they were identified as

$$K_S^0 = K_1^0 \qquad K_L^0 = K_2^0$$

# CP-violation in kaon sector

In 1964 $K_L^0 \to \pi^+\pi^-$ was observed with a tiny branching
ratio of ~ $10^{-3}$.
Since CP($K_L^0$) must be –1, this is an evidence for a small CP-violation. Thus, physical states $K_S^0$ and $K_L^0$ need
not correspond to the CP-eigenstates $K_1^0$ and $K_2^0$

$$\psi_{K_S^0}(\vec{p}=\vec{0}) = \frac{1}{\sqrt{(1+|\varepsilon|^2)}}\left[\psi_{K_1^0}(\vec{p}=\vec{0}) - \varepsilon\psi_{K_2^0}(\vec{p}=\vec{0})\right]$$

$$\psi_{K_L^0}(\vec{p}=\vec{0}) = \frac{1}{\sqrt{(1+|\varepsilon|^2)}}\left[\varepsilon\psi_{K_1^0}(\vec{p}=\vec{0}) + \psi_{K_2^0}(\vec{p}=\vec{0})\right]$$

where $\varepsilon$ is a small complex parameter

# CP-violation in kaon sector

- CP-violating decays can occur in two different ways
  - (a) CP-forbidden $K_1^0$ component in the $K_L^0$ decays via a CP-allowed process giving a contribution proportional to $|\varepsilon|^2$ of finding $K_1^0$ component in $K_L^0$
  - (b) CP-allowed $K_2^0$ component in the $K_L^0$ decays via a CP-violating reaction
- Detailed analysis shows (a) dominates with $|\varepsilon| \approx 2.2 \times 10^{-3}$
- Nowadays mixing in $B\bar{B}$ is also under study

# Strangeness oscillations

- $K^0\bar{K}^0$ mixing leads to strangeness oscillations
- If $K^0$ is produced with $S=+1$, then after traveling some distance L (or after some time t) it will no longer have definite S but components with both $S=+1$ and $S=-1$.
- This enables to measure mass difference between $K_S^0$ and $K_L^0$ with extraordinary precision
- The oscillations in kaon sector made Bruno Pontecorvo think and come up with the neutrino oscillations idea

# Strangeness oscillations

Consider K$^0$ produced in $\pi^- + p \rightarrow K^0 + \Lambda^0$

t = 0 when K$^0$ produced $S = \;\; 0 \;\;\; 0 \;\;\; 1 \;\;\; -1$

$$\psi_{K^0}(\vec{p}) = \frac{1}{\sqrt{2}}\left\{\psi_{K_S^0}(\vec{p}) + \psi_{K_L^0}(\vec{p})\right\}$$

At later times this will become

$$\psi_{K^0}(\vec{p}) = \frac{1}{\sqrt{2}}\left\{a_S(t)\psi_{K_S^0}(\vec{p}) + a_L(t)\psi_{K_L^0}(\vec{p})\right\} \text{ where } a_\alpha(t) = e^{-im_\alpha t}e^{-\Gamma_\alpha t/2} \quad (\alpha = S, L)$$

$m_\alpha$ and $\Gamma_\alpha$ are the mass and decay rate of the particle

For times $t$ such that $\tau_S \lll t \leq \tau_L$ ($\tau_{S,L} = \Gamma_{S,L}^{-1}$) only $K_L^0$ component survives

impying equal intensities $K^0$ and $\bar{K}^0$ components.

We can rewrite $\psi_{K^0}(\vec{p})$ as

$$\left\{A_0(t)\psi_{K^0}(\vec{p}) + \bar{A}_0(t)\psi_{\bar{K}^0}(\vec{p})\right\}$$

where $A_0(t) = \frac{1}{2}\left[a_S(t) + a_L(t)\right]$, $\bar{A}_0(t) = \frac{1}{2}\left[a_S(t) - a_L(t)\right]$

# Strangeness oscillations

The intensities of two components are then given by

$$I(K^0) \equiv \left|A_0(t)\right|^2 = \frac{1}{4}\left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-(\Gamma_S+\Gamma_L)t/2}\cos(\Delta m t)\right]$$

$$I(\bar{K}^0) \equiv \left|\bar{A}_0(t)\right|^2 = \frac{1}{4}\left[e^{-\Gamma_S t} + e^{-\Gamma_L t} - 2e^{-(\Gamma_S+\Gamma_L)t/2}\cos(\Delta m t)\right]$$

where $\Delta m = \left|m_S - m_L\right|$

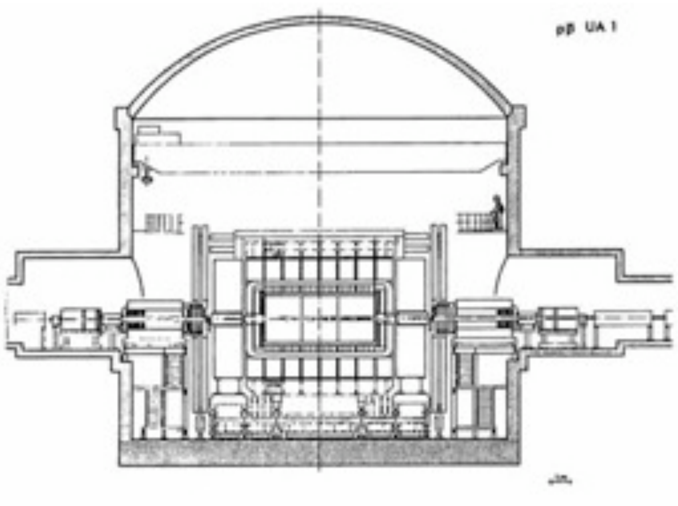
The variation of $I(\bar{K}^0)$ with time can be determined experimentally by measuring the rate of production of hyperons (baryons with S≠0)

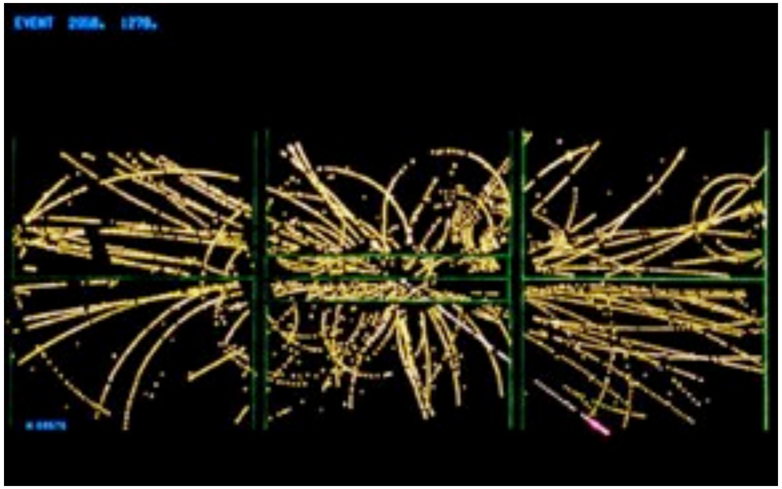
$$\bar{K}^0 + p \to \pi^+ + \Lambda^0 (\pi^0 + \Sigma^+)$$

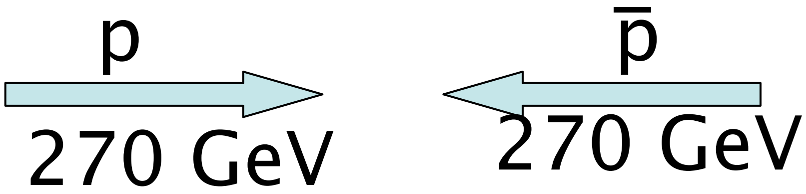
The result: $\Delta m = (3.522 \pm 0.016)\times 10^{-12}$ MeV/$c^2$

# Discovery of $W^{\pm}$ and $Z^0$ bosons (CERN, 1983)

## UA1 detector sketch and W event







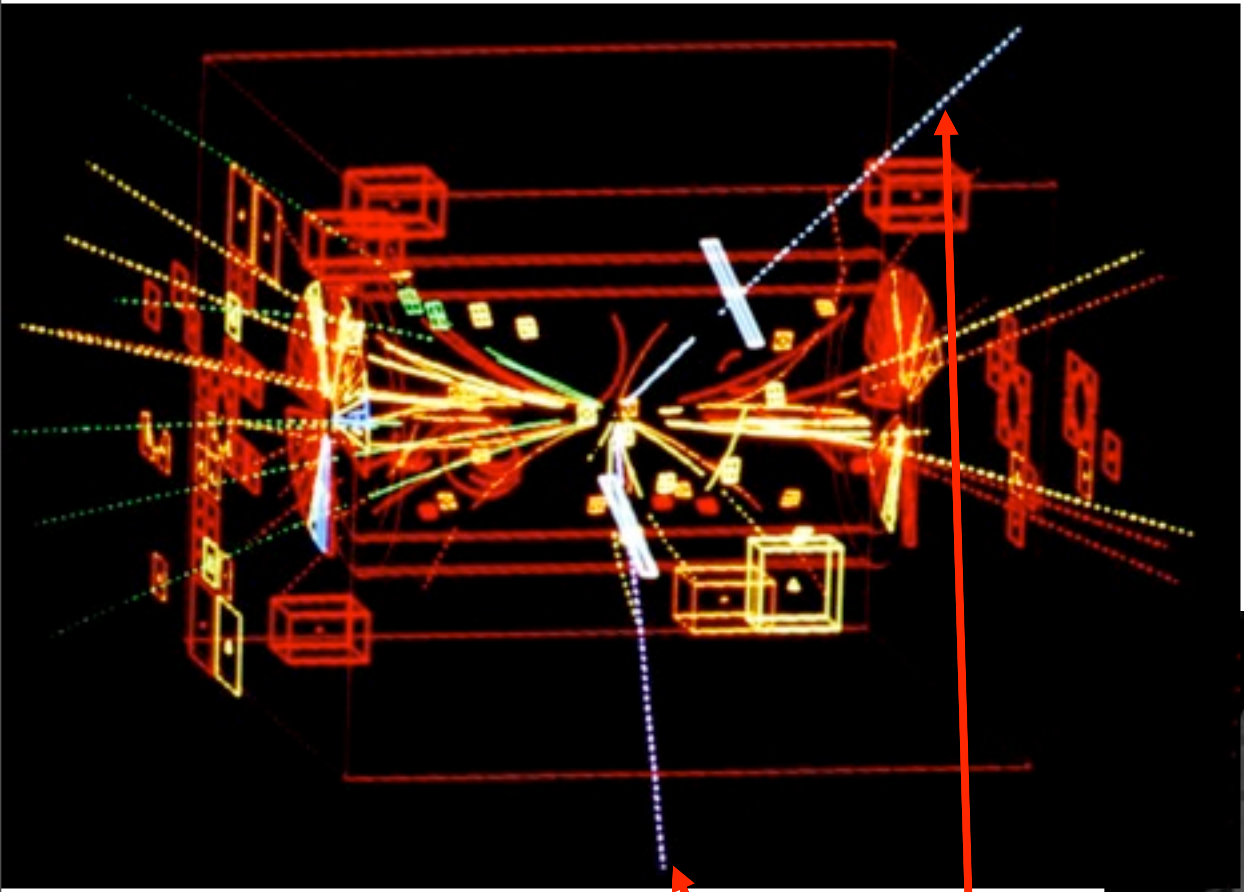
p

p̄

270 GeV

270 GeV

$$\overline{p} + p \text{ ® } W^{+} + X^{-}, \;\; \overline{p} + p \text{ ® } W^{-} + X^{+}, \;\; \overline{p} + p \text{ ® } Z^{0} + X^{0}$$



1984 Nobel prize to Carlo Rubbia and Simon Van Der Meer

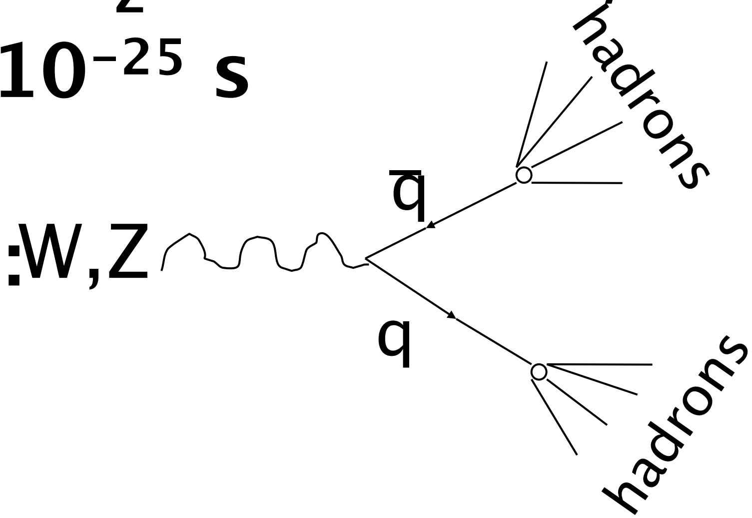
Cut on relatively large transverse momentum $p_T$ to select heavy particle produced in e+e- collision (Lighter particles will have smaller $p_T$ due to Lorentz boost)

# W and Z bosons

**$M_W = 80.6\ \mathrm{GeV}/c^2$, $M_Z = 91.2\ \mathrm{GeV}/c^2$**

**$\tau \approx 3\times10^{-25}$ s**

**Dominant decays:**



**Also leptonic decays:**

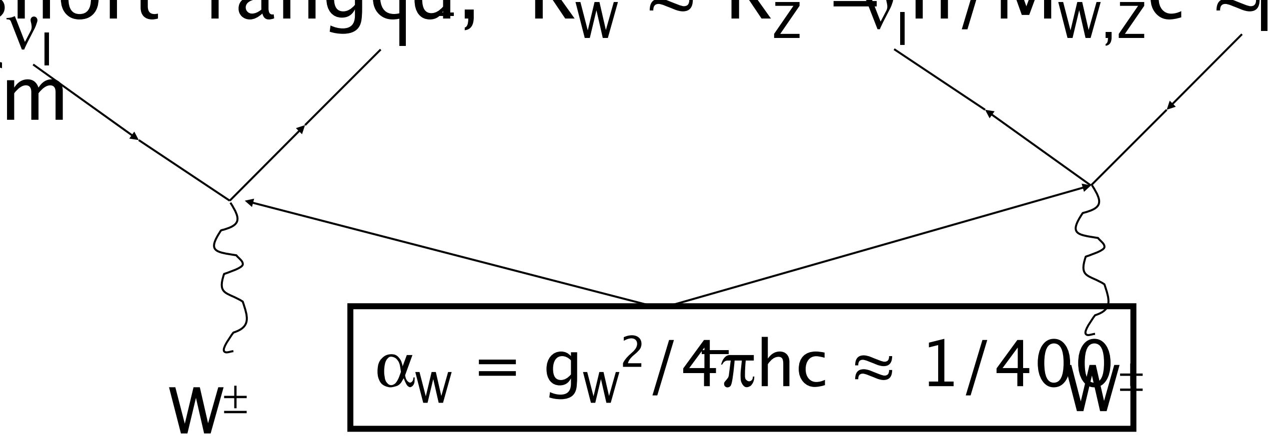
$W^+ \rightarrow l^+ + \nu_l$ $\quad$ $W^- \rightarrow l^{\overline{-}} + \nu_l$

$Z^0 \rightarrow l^+ + l^-$ $\quad$ $Z^0 \rightarrow \bar{\nu}_l + \nu_l$

**All leptonic decays conserve individual lepton numbers**

# W and Z bosons

Because W and Z are massive weak interactions are short-ranged, $R_W \approx R_Z = \hbar/M_{W,Z}c \approx 2\times10^{-3}$ fm



$$\boxed{\alpha_W = g_W^2/4\pi\hbar c \approx 1/400}$$

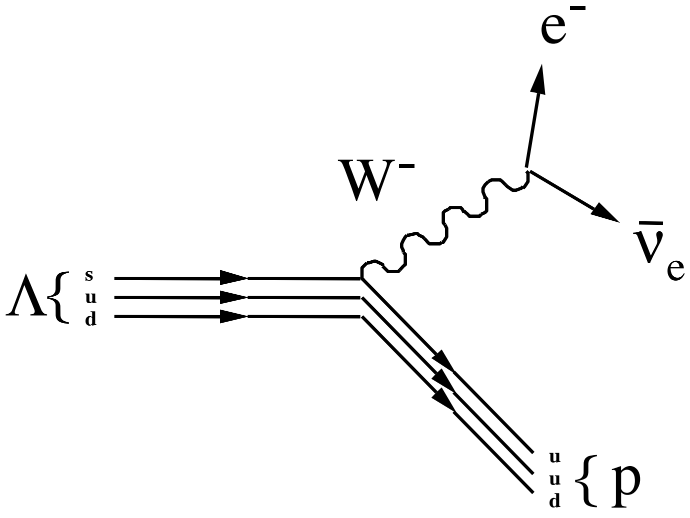
**Comparing $\alpha_w$(1/400) and $\alpha_{EM}$(1/137) we see that weak and EM interactions should have similar strength. The big difference at low energies is because exchange bosons, W,Z, are heavy**

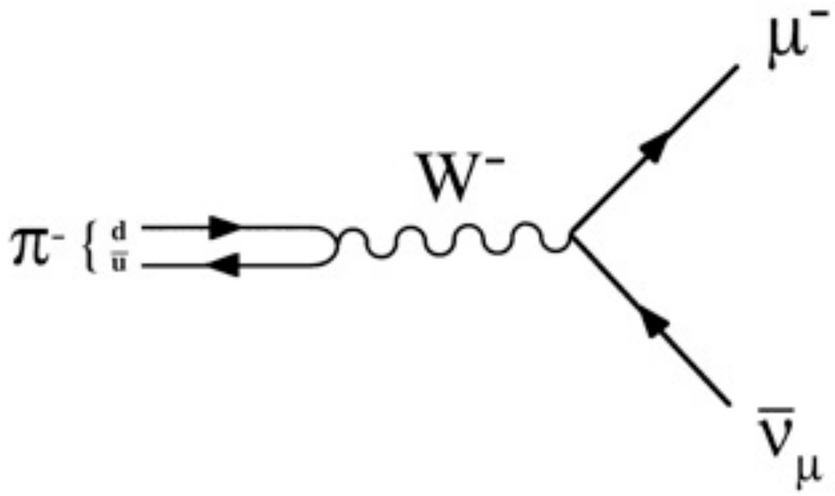
# W and Z bosons

- At energies where $\lambda=(h/p) >> R_{W,Z}$, the range can be neglected
- In this approximation the weak interaction becomes a point or zero range interaction with effective strength
- $\alpha_{eff} = \alpha_W(E/M_Wc^2)^2$, $E << M_Wc^2$
- where E is a typical energy scale of the process
- At energies on the scale of W,Z boson masses weak interaction strength becomes comparable to EM interaction strength

# Weak interactions of hadrons

- W-bosons emitted or absorbed by quarks





β–decay

$n \rightarrow p + e^- \overline{+} \nu_e$

or

$d \rightarrow u + e^- \overline{+} \nu_e$

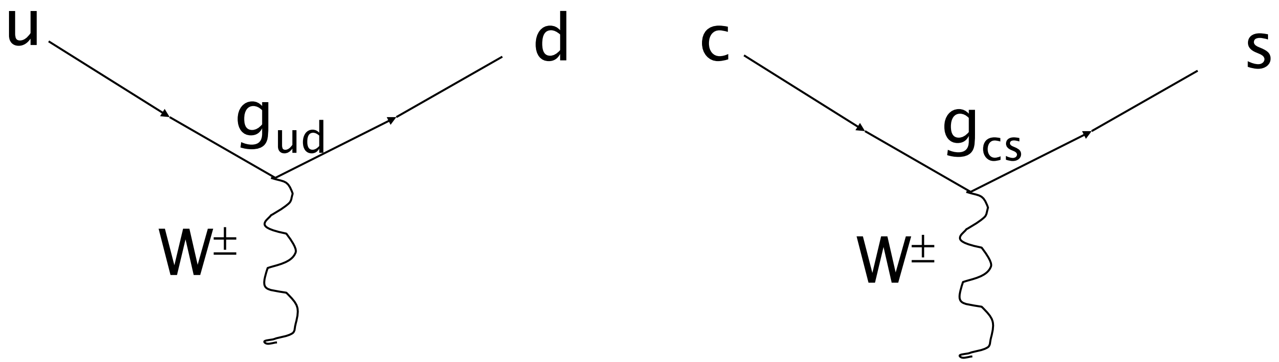
pion decay

$\pi^-(d\bar{u}) \rightarrow \mu^- \mp \nu_\mu$

# Lepton-quark symmetry of weak interactions. The idea.

- Taking for simplicity 2 generations

$$\underbrace{\begin{pmatrix} u \\ d \end{pmatrix} \text{ and } \begin{pmatrix} c \\ s \end{pmatrix} \leftrightarrow \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \text{ and } \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}}_{\text{have identical weak interactions}}$$



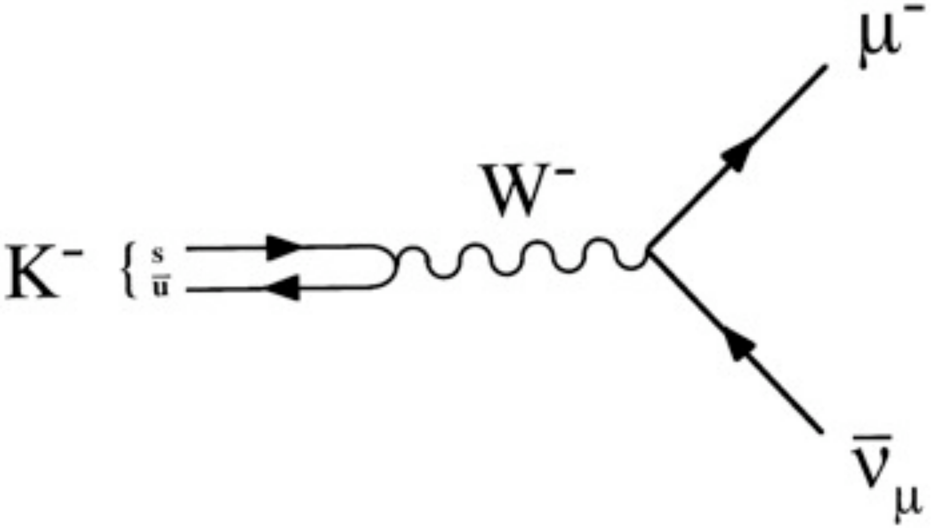
The same for $\bar{u}\ \bar{d}$, $\bar{c}\ s$

**$g_{ud} = g_{cs} = g_W$**

# Lepton-quark symmetry. The problem.

- Lepton–quark symmetry implies that $d+\bar{u}\rightarrow W^-$, $s+\bar{c}\rightarrow W^-$ "allowed" while $s+\bar{u}\rightarrow W^-$, $d+\bar{c}\rightarrow W^-$ "forbidden"
- This works fine for many decays ($\pi\rightarrow\mu\nu_\mu$)
- However, many "forbidden" decays are observed although at rates suppressed compared to "allowed" decays

Example: $K^- \rightarrow \mu^- + \bar{\nu}_\mu$



**In order to solve this problem quark mixing was introduced**

# Quark mixing

- d and s quarks participate in the weak interactions via the linear combinations (recall neutrino and kaon mixing)

  $d' = d \cos\theta_C + s \sin\theta_C$

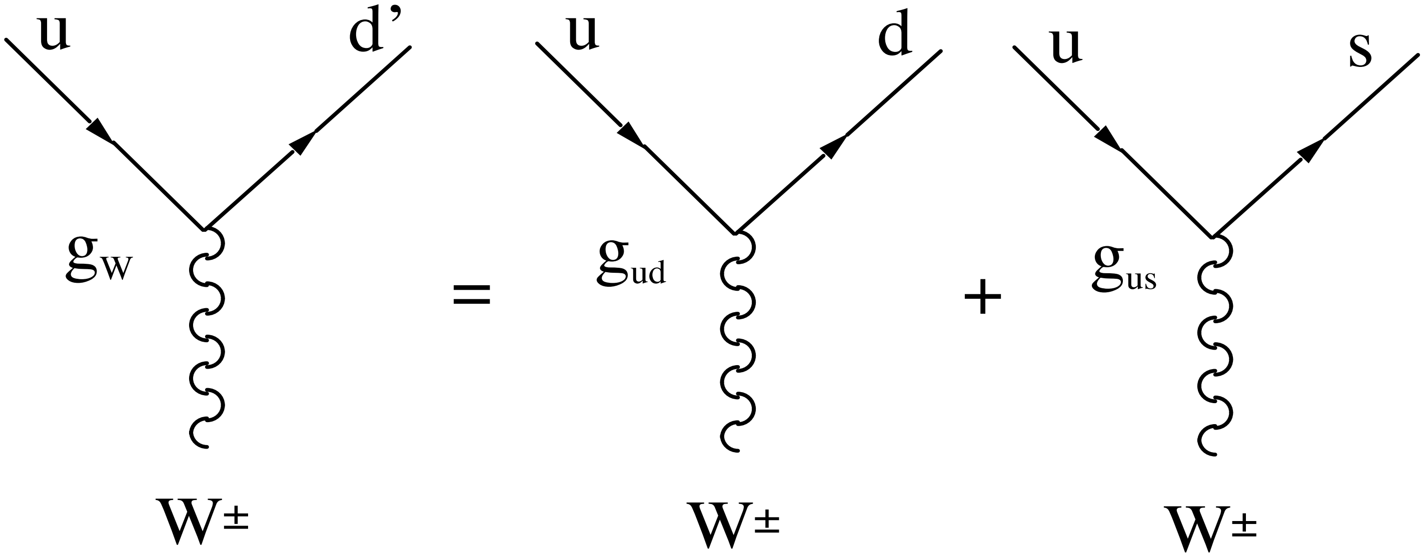
  $s' = -d \sin\theta_C + s \cos\theta_C$

  $\theta_C$ – Cabibbo angle

- Thus, lepton-quark symmetry is assumed to apply to the doublets

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} c \\ s' \end{pmatrix}$$

# Quark mixing



$g_{ud} = g_W\cos\theta_C$ $g_{us} = g_W\sin\theta_C$

$\theta_C = 13°$, providing good agreement with $K \rightarrow \mu\nu_\mu$
and other suppressed rate decays

# Charmed quark prediction

- By 1971 seven fundamental fermions were known: $\nu_e$, e, $\nu_\mu$, $\mu$, u, d, s
- Glashow, Iliopolous and Maiani proposed the existence of c-quark to complete the set

$$\begin{pmatrix} u \\ d \end{pmatrix} \qquad \begin{pmatrix} \boxed{c} \\ s \end{pmatrix} \qquad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \qquad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$$

- The charmed quark was discovered in 1974. Its measured weak couplings are consistent with the predictions of lepton-quark symmetry and quark mixing

# Quark mixing. Modern picture.

Now we know there are 3 generations

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}\quad\begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}\quad\begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}$$

$$\begin{pmatrix}u\\ d\end{pmatrix}\quad\begin{pmatrix}c\\ s\end{pmatrix}\quad\begin{pmatrix}t\\ b\end{pmatrix}$$

CKM matrix

$$CKM=\begin{pmatrix}c_1 & c_3s_1 & s_1s_3\\ -c_2s_1 & c_1c_2c_3-s_2s_3e^{i\delta} & c_1c_2s_3+c_3s_2e^{i\delta}\\ s_1s_2 & -c_1c_3s_2-c_2s_3e^{i\delta} & -c_1s_2s_3+c_2c_3e^{i\delta}\end{pmatrix}\qquad c_i=\cos\theta_i\,,\quad s_i=\sin\theta_i$$

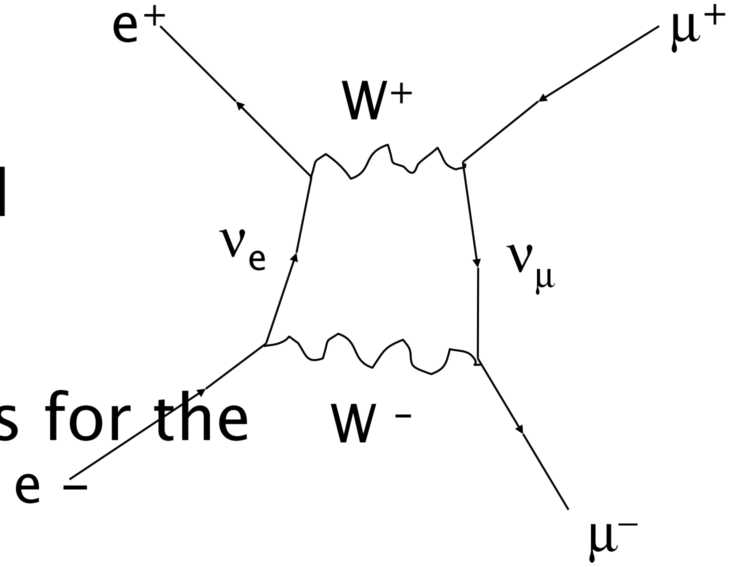
$\theta_{1,2,3}$ -- mixing angles (instead of $\theta_C$ in 2x2 matrix)

$\delta$ -- CP-violating phase. ← **Possibility to study CP-violation**

MNS mixing matrix for neutrinos was built based on CKM recipe

# Neutral currents and the unified electroweak theory

It was necessary to solve a problem associated with calculation of Feynman diagrams in which more than one W boson was exchanged (higher order processes)
These calculations led to divergences – infinite probabilities for the processes



In the unified theory the problem was solved when diagrams involving
the exchange of $Z^0$ bosons and photons were taken into account.
When all the diagrams of a given order are added together the

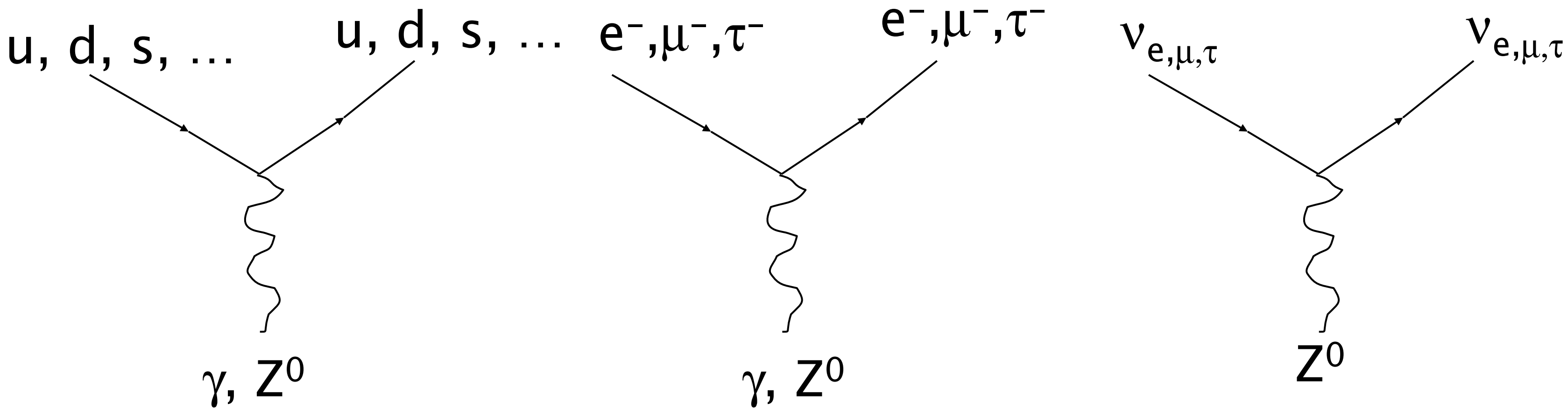
# Unification condition

- To ensure the divergences cancellation, the theory requires the unification condition

$$\frac{e}{2\sqrt{2\varepsilon_0}} g_W \sin\theta_W = g_Z \cos\theta_W$$

- $\theta_W$ – weak mixing angle (Weinberg angle) is given by $\cos\theta_W \equiv M_W/M_Z$

# $Z^0$ and $\gamma$ couplings to leptons and quarks

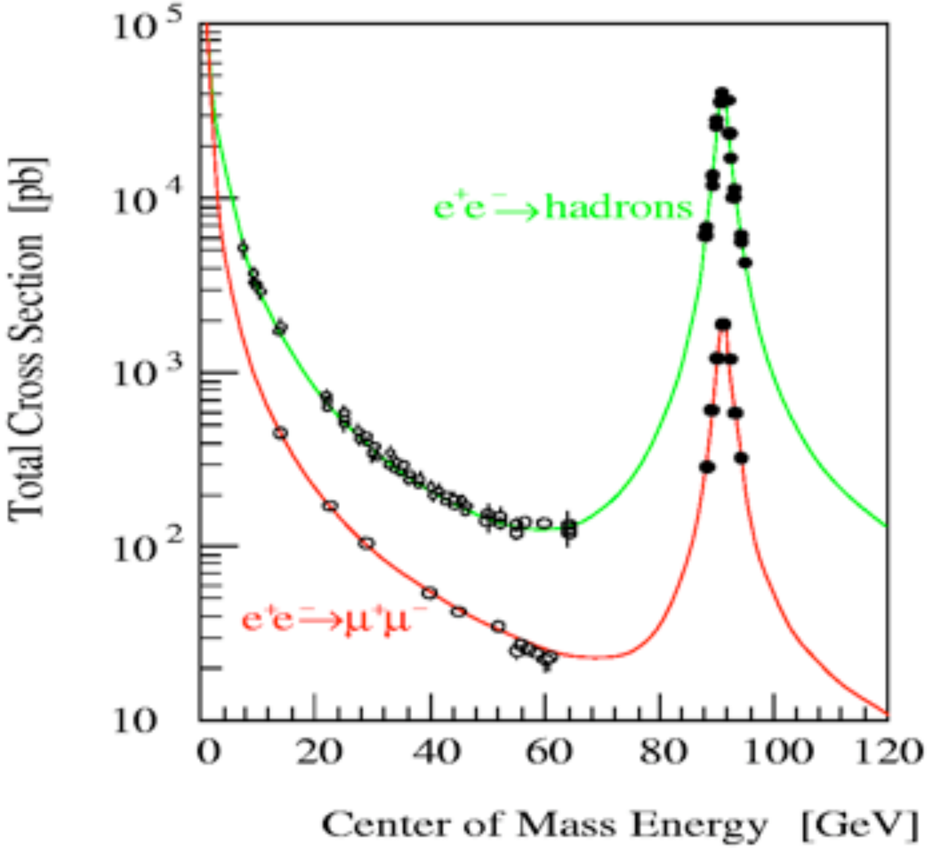


**Neutral current interactions, like EM interactions, individual quark numbers. Charged current intera do not.**

In any process where $\gamma$ is exchanged, $Z^0$ can be exch $Z^0$ contribution is not sizeable at low energies (E << but it is at high energies.

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

$$\frac{\sigma_Z}{\sigma_\gamma} = \frac{\alpha_Z^2 E^2 (\hbar c)^2}{(M_Z c^2)^4} \frac{E^2}{\alpha^2 (\hbar c)^2} \approx \frac{E^4}{(M_Z c^2)^4}$$



# Standard Model, Gauge Invariance and Higgs.

## Constructing the Standard Model

SM is a field theory. Describes force-matter interactions by Lagrangians.

$$L = -1/4 F_{\mu\nu} F^{\mu\nu} + \bar{\Psi}(i\gamma^{\mu} D_{\mu} - m)\Psi$$

Field strength of force field F

Boson-Fermion interaction. Fermion movement.

Fermion mass

Each force (EM, weak, strong) described by *L* of similar form (details of *F, D,* $\Psi$ vary)

$$\Psi \rightarrow e^{-i\theta(x,t)}\Psi$$

Lagrangian *L* obeys **local gauge invariance**

Doesn't change as a function of space and time:

Consequence that bosons ***must be massless***

# A few remarks about the Higgs boson

- Gauge invariance says that spin-1 gauge bosons must have zero mass if they are the only existing bosons
  - OK for QED and QCD but not for Weak. (W and Z are heavy!)
- This origin of mass problem is overcome by assuming that particles interact with the Higgs field
  - Gauge bosons acquire masses without violating gauge invariance
  - There are electrically neutral quanta of the Higgs field – Higgs bosons (spin-0)
- Full SM Lagrangian:

$$L_{SM} = \sum_{gauge\,bosons} -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \sum_{fermions} \bar{\psi} D \psi + (D_\mu \Phi)^+ (D^\mu \Phi) - V(\Phi)$$

Gauge boson interaction terms

Free particle term

Higgs field $\Phi$ terms (to give mass)

# A quasi-political Explanation of the Higgs Boson; for Mr Waldegrave, UK Science Minister 1993.

by David Miller (UCL)

# The Higgs mechanism 1

Imagine the vacuum in the form of a cocktail party of political workers, uniformly spread across the room.

The vacuum

# The Higgs mechanism 1

Imagine the vacuum in the form of a cocktail party of political workers, uniformly spread across the room.

The vacuum

Drawings by Georges Boixader.

Story by DJM

# The Higgs mechanism 2

A beloved ex prime-minister enters and is immediately surrounded by well-wishers.

# The Higgs mechanism 2

A beloved ex prime-minister enters and is immediately surrounded by well-wishers.

# The Higgs mechanism 2

A beloved ex prime-minister enters and is immediately surrounded by well-wishers.

The cluster of admirers gives her extra mass, i.e. more inertia; just as an electron acquires extra mass from the lattice in a semiconductor; or the W and Z from the Higgs

# The Higgs boson 1

A scandalous rumour is launched into the party.

# The Higgs boson 1

A scandalous rumour is launched into the party.

# The Higgs boson 2

The partygoers clump to transmit the rumour, just as they clumped around the ex-leaderine.

# The Higgs boson 2

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# The Higgs boson 2

The partygoers clump to transmit the rumour, just as they clumped around the ex-leaderine.

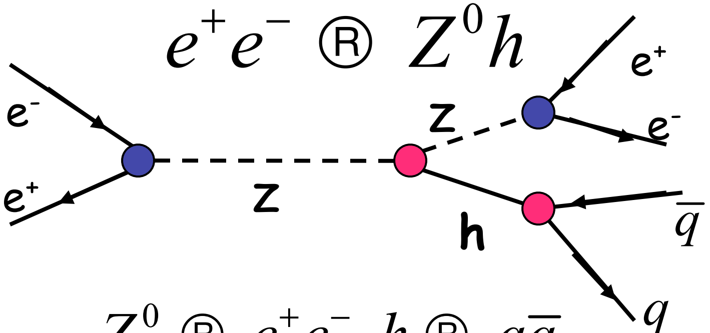
Similar "dilaton" effects occur in solids. The clump can travel like a particle.

In the vacuum such a clump in the Higgs field is a Higgs boson. It has spin=0.

# A LEP Higgs candidate event

Could have been

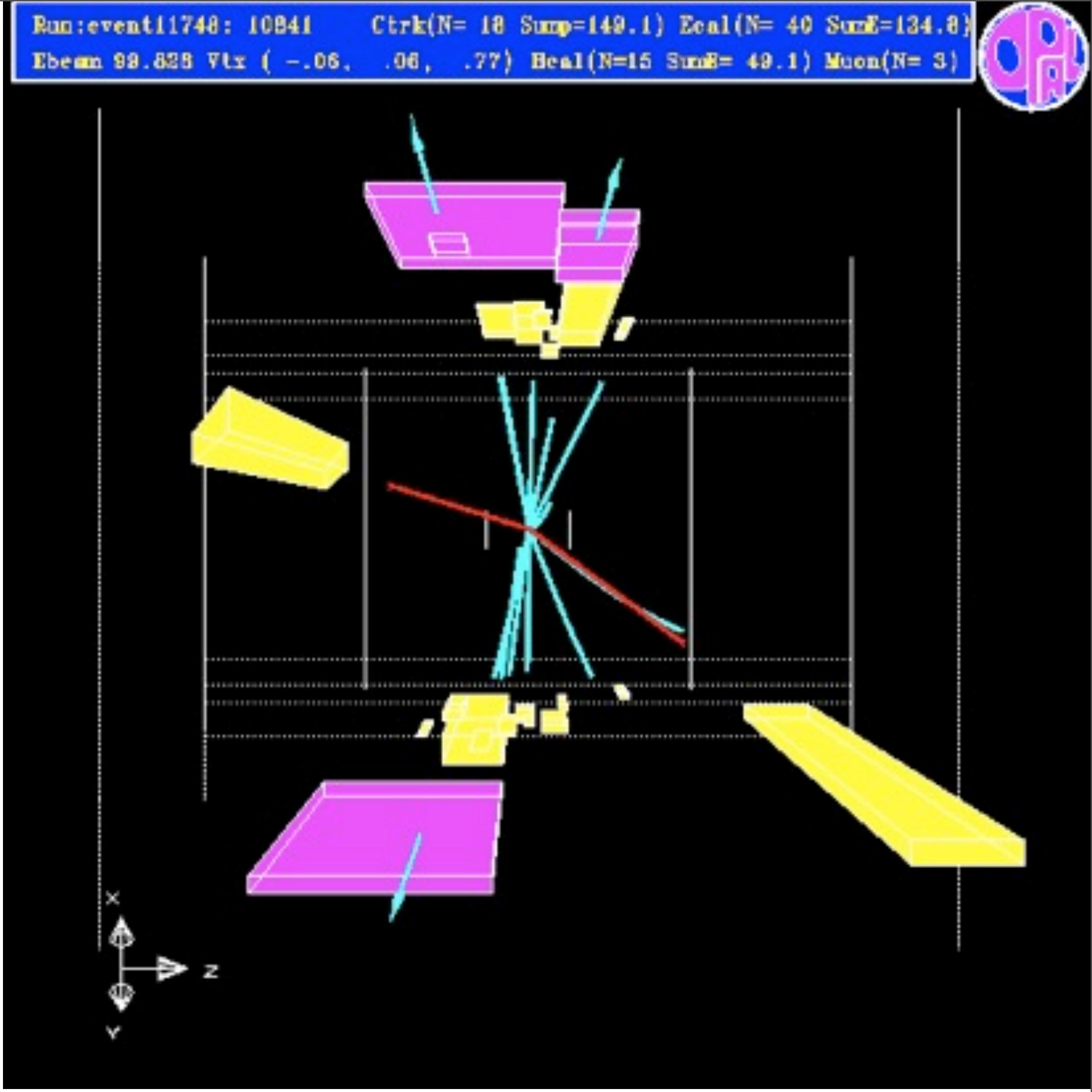
$e^+e^-$ ® $Z^0h$



$Z^0$ ® $e^+e^-, h$ ® $q\bar{q}$

The two red tracks, with yellow hits in the calorimeters

The two blue jets with multicoloured hits in the calorimeters



Or it could just have been

$e^+e^-$ ® $Z^0Z^0$

We did not have quite enough energy to be sure

LHC will take over in ~2009. Finding $H^0$ is one of the highest priorities in HEP

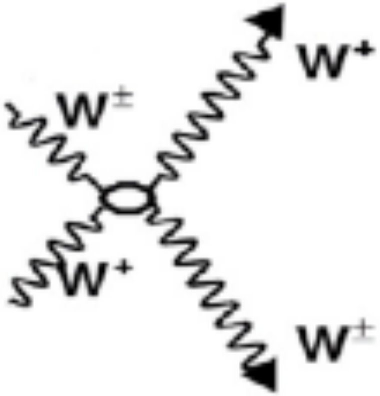
# A few remarks about the Higgs boson

- The existence of the Higgs boson is the most important prediction of the Standard Model which has not been experimentally verified yet
- Extensive searches: LEP (CERN) $e^+e^- \to H^0Z^0$

  saw some indication on $H^0$ but not statistically convincing
- LHC will take over in ~2008. Finding $H^0$ is one of the highest priorities in HEP

# What if we do not see Higgs at LHC?..

If no Higgs with $m_H$ < 1 TeV there must be **New Physics** to keep WW scattering finite



Then..

- It does not exist
- Or it is too heavy to make

With $E_{CM}$ = 14 TeV at LHC discovery is “guaranteed”

Many suggestions for **New Physics**.
**Supersymmetry (SUSY)** is among favourites