6. Detection of W and Z – bosons

Discovery: p + p̄ with collider (SPPS) at 318 GeV (1983),
→ Carlo Rubbia, Simon van der Meer (Nobelprize 1984)
SPS (Super Proton Synchrotron) modified to
SPPS (Super Proton anti-Proton Synchrotron)
with stochastic cooling

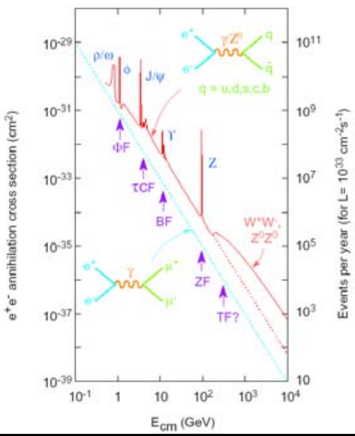
Method:

$Z^0 \rightarrow e^+ + e^-$ **Reconstruction of invariant mass**

$Z^0 \rightarrow \mu^+ + \mu^-$

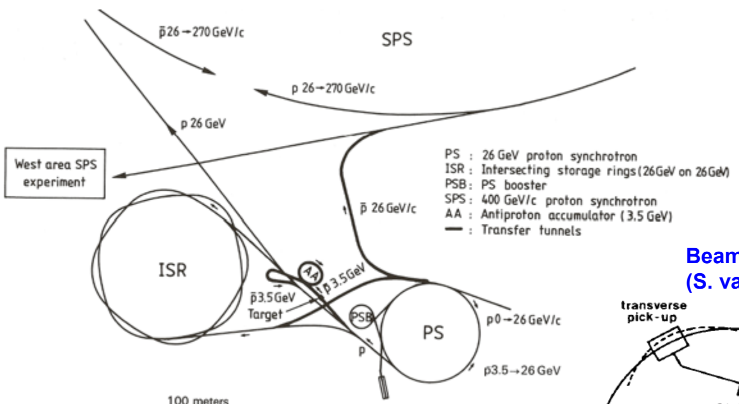
$W^+ \rightarrow e^+ + \nu_e$ **Missing momentum analysis**

$W^+ \rightarrow \mu^+ + \nu_\mu$



Precision experiments: LEP **>1989 Z^0**
>1996 W^+W^-

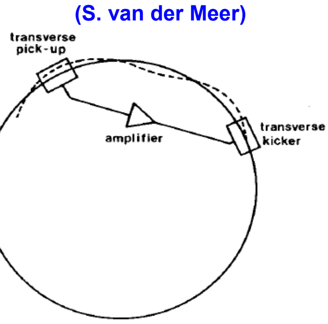
6. SPS – machine



Energies:

Linac	50 MeV
Booster	1.4 GeV
PS	26 GeV
SPS	450 GeV

Beam cooling (in AA)
(S. van der Meer)



Antiproton production:

$$p(26GeV) \rightarrow Cu \ \ \text{target} \xrightarrow{\frac{n(\bar{p})}{n(p)}=10^{-6}} \bar{p}(3.5GeV) \xrightarrow{\text{stacked (each 2.4s)}} AA \xrightarrow{10^{11}/d} PS$$

6.

UA1 - detector

C. Rubbia

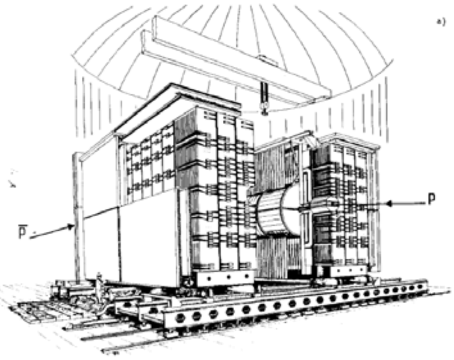
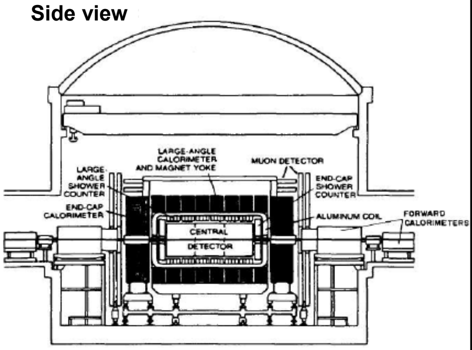


Fig. 8a. The UA1 detector solid-angle is fully covered down to 0.2°.

Side view



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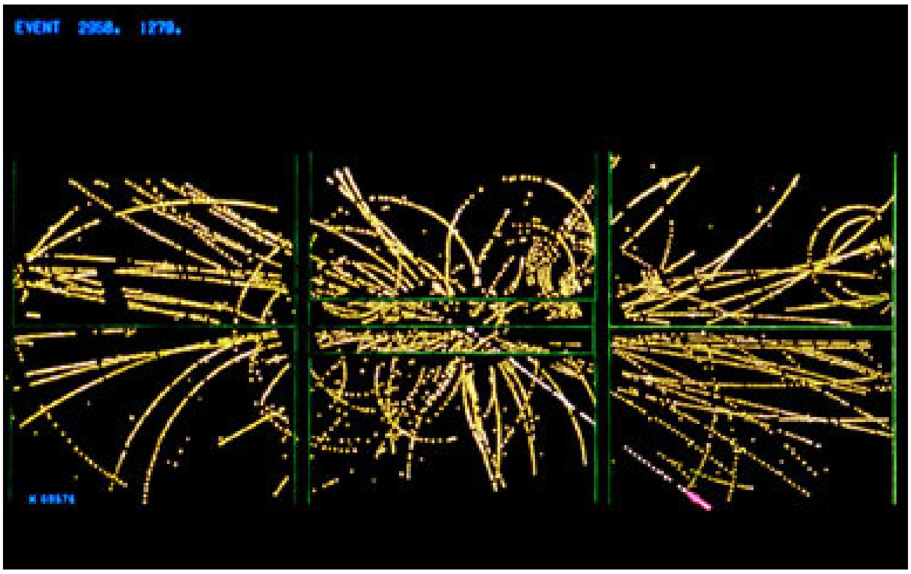
6.

W – event



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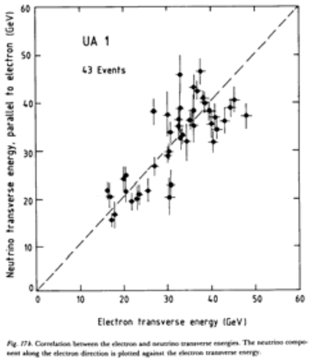
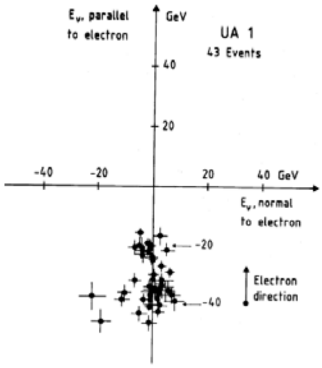
6.

W – results (UA1)

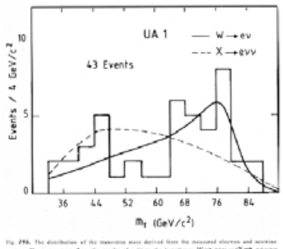
1983

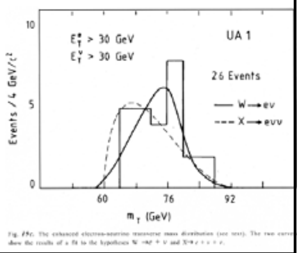




m_W = (80,9 ± 1,5) GeV

PDG(2011): 80,399 +/- 0.023 GeV





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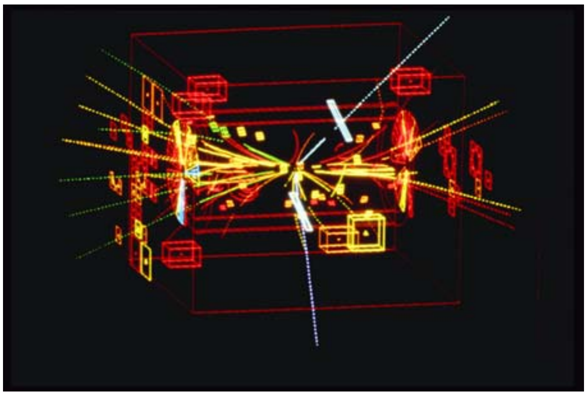
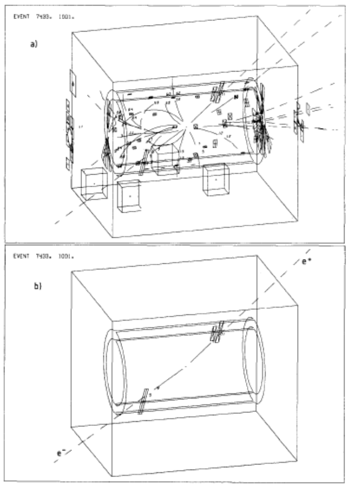
6.

Z^0– Event (UA1)

1983





- Example of the event with electron pair: when a cut p_T > 2 GeV for tracks in the central detector and E_T > 2 GeV in the calorimeters, two high-energy electron-positron tracks become evident.

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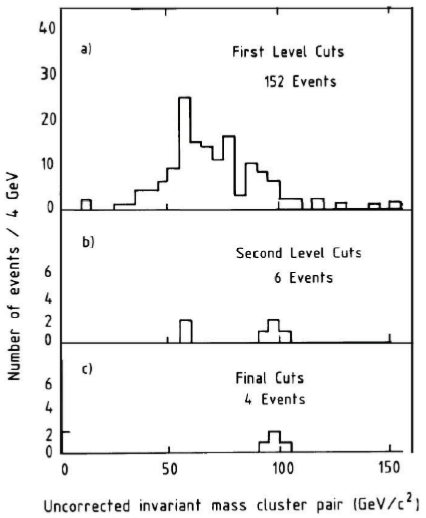
6.

Z^0– results (UA1)

1983



E_T>25GeV

ΔE<800MeV

Isolated tracks

$m_z = (95{,}2 \pm 2{,}5)$ GeV

6.1

Properties of W – bosons

Charged current interaction: $W^{+/-}$

Universality of CC interaction
⇔Coupling to LH fermions and RH anti-fermions with universal strength

Consider branching ratios of W^+ - decays:

Possible channels:

W^+
- $\rightarrow e^+ \nu_e$
- $\rightarrow \mu^+ \nu_\mu$
- $\rightarrow \tau^+ \nu_\tau$
- $\rightarrow u\, \bar{d}'$ **(x3 due to color)**
- $\rightarrow c\, \bar{s}'$ **(x3 due to color)**

(no top decay possible because of mass)

Experimental results: (PDG 2011)

$$BR(e^+\nu_e) = 10.75 \pm 0.13\%$$
$$BR(\mu^+\nu_\mu) = 10.57 \pm 0.15\%$$
$$BR(\tau^+\nu_\tau) = 11.25 \pm 0.20\%$$

Conclusion: **expectation of BR = 1/9 fits very well.**

6.1

Properties of Z – Bosons

Neutral current (NC) interaction Strom: Z^0

Universality of weak interaction (?)

⇔ Coupling to all fermion / anti-fermion pairs with universal strength

Possible decay channels of Z^0:

Z^0 → 3 charged lepton/anti-lepton pairs
→ 3 neutrino / anti-neutrino pairs
→ 5 quark/anti-quark pairs (x3 due to color)

Total: 21 equally weighted decay channels (1/21=0.048)

Experimental: (PDG 2011)

$$BR(Z^0 \to e^+e^-) = 3.363 \pm 0.004\%$$
$$BR(Z^0 \to \mu^+\mu^-) = 3.366 \pm 0.007\%$$
$$BR(Z^0 \to \tau^+\tau^-) = 3.367 \pm 0.008\%$$
$$BR(Z^0 \to \nu\bar{\nu}) = 20.00 \pm 0.06\%$$
$$BR(Z^0 \to \text{hadrons}) = 69.91 \pm 0.06\%$$

BRs not compatible with 4.8% each.

Coupling depends on electric charge of particles.

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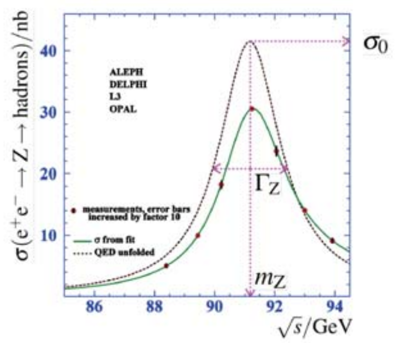
6.1

Measurement von $Z^0 \to$ Neutrino/Antineutrino



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$$\sum_i \Gamma_i = \Gamma = \frac{1}{\tau}$$
$$B_i = \frac{\Gamma_i}{\Gamma} \text{ (branching ratio)}, \qquad \sum_i B_i = 1$$

Breit-Wigner Form of cross section:

$$\sigma_{i\to f}(s) = \frac{12\pi\, s}{m_Z^2}\,\frac{\Gamma_i\Gamma_f}{\left(s - m_Z^2\right)^2 + m_Z^2\Gamma^2}$$

All channels show a resonance peaked at M_Z with total width Γ.

Peak cross section measures Γ_f.

Subtracting the sum of all charge leptonic and hadronic partial widths from the total width gives access to the number of neutrino generation (provided $\Gamma_{\nu\nu}$ is known).

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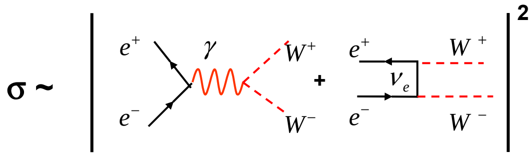
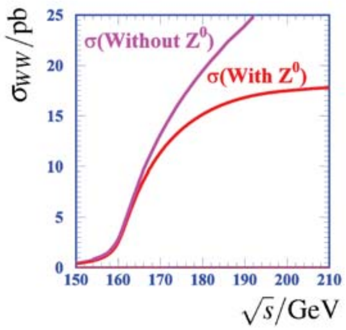
6.1

Z^0 – coupling

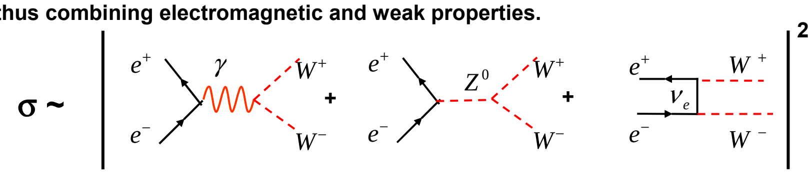
Unitarity problem in W+W-





Solution:

Z- boson has to couple to W in a way to cancel the divergent cross section, thus combining electromagnetic and weak properties.



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5.3

V-A coupling of leptons and quarks

Weak interactions are described by V-A theory
that couples left handed (LH) lepton and quark currents.
[RH for antiparticles]

Coupling occurs with universal strength in LH 'weak-isospin' doublets

Lepton currents

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix} \quad j^\mu_{e\nu} = \bar{u}_e\gamma^\mu\left(1-\gamma^5\right)u_\nu$$

$$\begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix} \quad j^\mu_{\mu\nu} = \bar{u}_\mu\gamma^\mu\left(1-\gamma^5\right)u_\nu$$

$$\begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix} \quad j^\mu_{\tau\nu} = \bar{u}_\tau\gamma^\mu\left(1-\gamma^5\right)u_\nu$$

Quark currents

$$\begin{pmatrix}u\\ d'\end{pmatrix} \quad j^\mu_{d'u} = \bar{u}_{d'}\gamma^\mu\left(1-\gamma^5\right)u_u$$

$$\begin{pmatrix}c\\ s'\end{pmatrix} \quad j^\mu_{s'c} = \bar{u}_{s'}\gamma^\mu\left(1-\gamma^5\right)u_c$$

$$\begin{pmatrix}t\\ b'\end{pmatrix} \quad j^\mu_{b't} = \bar{u}_{b'}\gamma^\mu\left(1-\gamma^5\right)u_t$$

↑ not equal to mass eigenstates

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6.1

Symmetry of weak interaction

Weak interaction couples to doublets → SU(2) symmetry group = "weak isospin T"

Invariance under local phase transformations:

$$\psi' = e^{i\vec{\alpha}(x)\cdot\frac{\vec{\sigma}}{2}}\psi$$

σ_i are the generators (Pauli – matrices), α_i - parameter

$$\begin{pmatrix}\nu_e \\ e^-\end{pmatrix}_L' = e^{i\vec{\alpha}(x)\cdot\frac{\vec{\sigma}}{2}}\begin{pmatrix}\nu_e \\ e^-\end{pmatrix}_L$$

Weak interaction couples only to LH particles and RH anti – particles (LH/RH refers to chiral states)

RH articles and LH anti-particles form weak isospin singlets

Weak isospin structure of particles states:

T	T_3	particle state
$\frac{1}{2}$	$+\frac{1}{2}$, $-\frac{1}{2}$	$\begin{pmatrix}\nu_e \\ e^-\end{pmatrix}_L$
0	0	$(\nu_e)_R$
0	0	$(e^-)_R$

6.1

Currents of weak interaction

Define:

$$\chi_L = \begin{pmatrix}\nu_e \\ e^-\end{pmatrix}_L$$

Generators of the symmetry group specify the form of the interaction.
There is one term for each generator:

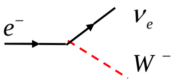
$$j_\mu^i = g_W \bar{\chi}_L \gamma^\mu \tfrac{1}{2}\sigma_i \chi_L$$

CC – interaction ($W^{+/-}$) enters as linear combination of W^1,W^2 corresponding to j_1,j_2:

$$j_\pm^\mu = g_W \frac{1}{\sqrt{2}}\left(j_1^\mu \pm i j_2^\mu\right) = \frac{g_W}{\sqrt{2}}\bar{\chi}_L\gamma^\mu \tfrac{1}{2}(\sigma_1 \pm i\sigma_2)\chi_L = \frac{g_W}{\sqrt{2}}\bar{\chi}_L\gamma^\mu\sigma_\pm\chi_L$$

(The bars indicate the adjoint spinors)

Ex.: W^- - exchange



$$j_+^\mu = \frac{g_W}{\sqrt{2}}\bar{\chi}_L\gamma^\mu\sigma_+\chi_L = \frac{g_W}{\sqrt{2}}\left(\bar{\nu}_e, \overline{e^-}\right)_L\gamma^\mu\begin{pmatrix}0 & 1 \\ 0 & 0\end{pmatrix}\begin{pmatrix}\nu_e \\ e^-\end{pmatrix}_L = \frac{g_W}{\sqrt{2}}\bar{\nu}_L\gamma^\mu e_L = \frac{g_W}{\sqrt{2}}\bar{\nu}\gamma^\mu \tfrac{1}{2}\left(1-\gamma^5\right)e$$

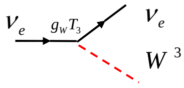
6.1

Neutral current in weak interaction

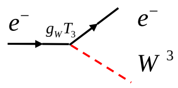
W^3 exchange -> j_3:

$$j_3^\mu = g_W \bar{\chi}_L \gamma^\mu \tfrac{1}{2} \sigma_3 \chi_L = \frac{g_W}{2} \left(\bar{\nu}_e, \overline{e^-}\right)_L \gamma^\mu \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$$

$$= g_W \tfrac{1}{2} \bar{\nu}_L \gamma^\mu \nu_L - g_W \tfrac{1}{2} \bar{e}_L \gamma^\mu e_L$$



T_3 = + 1/2



T_3 = - 1/2

However, the physical NC – bosons (γ,Z) are a mixture of W^3 and a new Boson B.

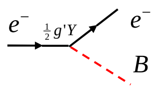
$$A_\mu = B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W$$
$$Z_\mu = -B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W$$

θ_W – weak mixing angle, Weinberg angle

The B – meson is associated with a new U(1) symmetry conserving the weak hypercharge Y.

$$Y = 2\mathrm{Q} - 2\mathrm{T}_3$$

(Gell-Mann Nishijima formula)



e_L: Y=2(-1)-2(-1/2) =-1
e_R: Y=2(-1)-2(0) =-2

ν_L: Y=-1
ν_R: Y=0

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6.1

Coupling constants for NC with electrons

Possible neutral currents:

$$j_3^\mu = -g_W \tfrac{1}{2} \bar{e}_L \gamma^\mu e_L$$
$$j_{e.m.}^\mu = e\bar{e}_L Q \gamma^\mu e_L + e\bar{e}_R Q \gamma^\mu e_R$$
$$j_Y^\mu = g' \tfrac{1}{2} \bar{e}_L Y \gamma^\mu e_L + g' \tfrac{1}{2} \bar{e}_R Y \gamma^\mu e_R$$

Weinberg angle:

$$j_{e.m.}^\mu = j_Y^\mu \cos\theta_W + j_3^\mu \sin\theta_W$$
$$e\bar{e}_L Q \gamma^\mu e_L + e\bar{e}_R Q \gamma^\mu e_R = g' \tfrac{1}{2} \cos\theta_W \left(\bar{e}_L Y \gamma^\mu e_L + \bar{e}_R Y \gamma^\mu e_R\right) - g_W \tfrac{1}{2} \sin\theta_W \bar{e}_L \gamma^\mu e_L$$
$$\Updownarrow$$
$$-e\bar{e}_L \gamma^\mu e_L - e\bar{e}_R \gamma^\mu e_R = g' \tfrac{1}{2} \cos\theta_W \left(-\bar{e}_L \gamma^\mu e_L - 2\bar{e}_R \gamma^\mu e_R\right) - g_W \tfrac{1}{2} \sin\theta_W \bar{e}_L \gamma^\mu e_L$$
$$\Downarrow$$

For LH and RH components:

$$-e = -g' \tfrac{1}{2} \cos\theta_W - g_W \tfrac{1}{2} \sin\theta_W$$
$$-e = -g' \cos\theta_W$$
$$\Downarrow$$
$$e = g' \cos\theta_W = g_W \sin\theta_W$$

Couplings of e.m., weak and Y – interaction are related!

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6.1

Z – boson coupling

Possible neutral currents:

$$j_3^\mu = -g_W \tfrac{1}{2} \bar{e}_L \gamma^\mu e_L$$

$$j_{e.m.}^\mu = e\bar{e}_L Q \gamma^\mu e_L + e\bar{e}_R Q \gamma^\mu e_R$$

$$j_Y^\mu = g' \tfrac{1}{2} \bar{e}_L Y \gamma^\mu e_L + g' \tfrac{1}{2} \bar{e}_R Y \gamma^\mu e_R$$

Weinberg angle:

$$Z_\mu = -B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W$$

$$j_{Z.}^\mu = -j_Y^\mu \sin\theta_W + j_3^\mu \cos\theta_W$$

$$= -g' \tfrac{1}{2} \sin\theta_W \left(\bar{e}_L \underbrace{Y}_{2(Q-T_3)} \gamma^\mu e_L + \bar{e}_R \underbrace{Y}_{2Q} \gamma^\mu e_R \right) \underbrace{-\tfrac{1}{2}}_{T_3} g_W \cos\theta_W \bar{e}_L \gamma^\mu e_L$$

$$= \left(-g' Q \sin\theta_W + g' T_3 \sin\theta_W + g_W T_3 \cos\theta_W \right) \bar{e}_L \gamma^\mu e_L - \left(g' Q \sin\theta_W \right) \bar{e}_R \gamma^\mu e_R$$

$$\downarrow e = g' \cos\theta_W = g_W \sin\theta_W$$

$$= g' \left(\frac{T_3 - Q\sin^2\theta_W}{\sin\theta_W} \right) \bar{e}_L \gamma^\mu e_L - g' \left(\frac{Q\sin^2\theta_W}{\sin\theta_W} \right) \bar{e}_R \gamma^\mu e_R$$

$$\downarrow g_Z = \frac{g'}{\sin\theta_W} = \frac{g_W}{\cos\theta_W}$$

$$= g_Z \underbrace{\left(T_3 - Q\sin^2\theta_W \right)}_{c_L} \bar{e}_L \gamma^\mu e_L - g_Z \underbrace{Q\sin^2\theta_W}_{-c_R} \bar{e}_R \gamma^\mu e_R$$

Z – boson couples with different strength to LH and RH fermions.