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# Summer School on Particle Physics in the LHC Era

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## Neutrinos and their manifestations

Francesco VISSANI
*Istituto Nazionale di Fisica Nucleare*
*Laboratorio Nazionale del Gran Sasso (L.N.G.S.)*
*S.S. 17 Bis Km. 18+910, Assergi, 67010*
*L'Aquila*
*Italy*

# NEUTRINOS

(1) Neutrinos as particles

Their mass, their number, their mixing, their magnetic moment, ...

(2) Neutrinos as observable radiation

Their detectable sources:

— $\pi^{\pm}$ from hadronic collisions (e.g., cosmic rays in Earth atm.; accelerators, ...)

Nuclear reactions (the sun, Earth radioactivity, core collapse supernovae, reactors, ...)

This course: mostly the first point of view (but the two are linked and the second is quite interesting, indeed)

Assume general knowledge of Standard Model (SM) of elementary particles and interactions (but we recall the relevant points when we use them).

# NEUTRINOS AS MISSING ENERGY

SINCE THE EARLY DAYS, NEUTRINOS ARE MOST COMMONLY SEEN AS "MISSING ENERGY".

(1) **β DECAYS:**

$$(A,Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e$$

WITHOUT $\bar{\nu}_e$, ONE WOULD FIND A MONOENERGETIC SPECTRUM. NEUTRINOS ALSO CARRY AWAY SPIN.

(2) **DECAY OF YUKAWA MESON**

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

THIS CAN BE SEEN, E.G., IN EMULSIONS SOMETHING LIKE


(3) **TOP DECAY**

$$t \ \bar{t} \rightarrow \bar{b}\, l\, \bar{\nu}_l$$

$$t \rightarrow b\text{-jet-jet}$$

THE BOTTOM CAN BE TRACKED WITH SPECIAL DEVICES AS "SILICON VERTEX", THE SEMILEPTONIC DECAY OF $\bar{t}$ INVOLVES NEUTRINOS, THUS $(p_b + p_l)^2 \neq m_t^2$ WHEREAS FOR THE HADRONIC DECAY, $(p_b + p_{J_1} + p_{J_2})^2 = m_t^2$.

## WEAK INTERACTIONS

$$\sigma \sim G_F^2\, s \sim 10^{-10}\,\mathrm{GeV}^{-4} \cdot \mathrm{GeV}^2\, \frac{E_\nu}{\mathrm{GeV}} \sim 10^{-38}\,\mathrm{cm}^2 \left(\frac{E_\nu}{\mathrm{GeV}}\right)$$

where $\hbar c \simeq 200$ MeV · fm.

$$\lambda \approx \frac{1}{\sigma \rho} = \frac{10^{38}\,\mathrm{cm}^{-2}}{6\, 10^{23}/\mathrm{cm}^3} \sim 10^{14}\,\mathrm{cm}\left(\frac{\mathrm{GeV}}{E}\right)$$

for comparison, $R_\oplus = 7000$ km $\sim 10^9$ cm.

The only $\nu$'s seen up to date:

100 keV < solar $\nu$ < SN $\nu$ reactor < atm. $\nu$ < accelerator < 1 TeV

The $\nu$ detectors must be big!

### REMARKS ON $\nu$ - hadron INTERACTIONS

At low energies, $\sigma \sim G_F^2 \cdot E_\nu^2$ ~~dominated by~~ ~~phase~~ regulated by phase space behaviour;

at higher energies, $E_\nu^2 \to s \sim m_p \cdot E_\nu$ in the case of scattering of $\nu$ and hadrons;

at still higher energies, $E_\nu \sim 10$ TeV, it is not adequate to treat the W as pointlike.

EXERCISE: (1) Estimate why $E_\nu \sim 10$ TeV.

(2) Consider $\mathcal{M} = \frac{G_F}{\sqrt{2}}\, \overline{u}_p(\gamma^a - 1.3\gamma^a\gamma^5)u_n \cdot \overline{u}_e(\gamma^a - \gamma^a\gamma^5)v_{\nu_e}$ for neutron decay: calculate the decay rate.

# HOW LARGE SHOULD DETECTOR BE? AN EXAMPLE

• LET US CONSIDER ~10 MeV $\bar{\nu}_e$ THAT INTERACT WITH FREE PROTONS VIA THE BASIC REACTION:

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

("inverse β decay", SINCE IT IS ONE OF THE CROSSED CHANNELS OF neutron β decay).

• THE NUMBER OF FREE PROTONS IN 1 kton OF WATER (= $H_2O$, 2 proton each molecule) is

$$N_p = \frac{2}{18} \times 10^3 \times 10^6 \times 6\, 10^{23} \sim \frac{2}{3}\cdot 10^{32}.$$

THE CROSS SECTION IS ABOUT $\sigma \sim 10^{-41}\ cm^2$.

THUS, THE NUMBER OF INTERACTIONS IS

$$N_{int.} = F_{\bar{\nu}_e} \times \sigma_{\bar{\nu}_e p} \times N_p = \frac{F_{\bar{\nu}_e}}{1.5\cdot 10^{9}\ cm^{-2}}$$

WE SEE THAT THE FLUENCE OF $\bar{\nu}_e$ SHOULD BE PRETTY LARGE, IN ORDER TO ~~HAVE~~ OBSERVABLE EVENTS.

• LET US ESTIMATE THE FLUENCE OF $\bar{\nu}_e$ FOR A SN. THE ENERGY OF A CORE COLLAPSE INTO A NEUTRON STAR OF ONE SOLAR MASS IS:

$$\mathcal{E} \sim \frac{G_N M_\odot^2}{R_{N.S}} = \frac{7\cdot 10^{-8}\,(2\cdot 10^{33} gr)^2}{(10\ km)^2} = \frac{7\,10^{-8}\, 4\,10^{66}}{10^6} \sim 3\,10^{53}\ erg$$

IT IS CARRIED AWAY BY THE 6 TYPES OF NEUTRINOS OF ~ 10 MeV

$$N_{\bar{\nu}_e} \sim \frac{3\,10^{53}}{6 \times 10 \times 1.6\,10^{-6}} \sim 3\,10^{57}\ \bar{\nu}_e$$

A TYPICAL DISTANCE IS $D \sim 10\ kpc = 10 \cdot 3 \cdot 10^3 \left(\pi 10^7 \cdot 3\,10^{10}\right) = 3\,10^{22}$ c

THUS THE $\bar{\nu}_e$ FLUENCE IS

$$F_{\bar{\nu}_e} \sim \frac{N_{\bar{\nu}_e}}{4\pi D^2} \sim \frac{3\,10^{57}}{4\pi (10^{22})^2 \cdot 10} \sim 2\,10^{11}\ \frac{\bar{\nu}_e}{cm^2}$$

WE EXPECT SOME HUNDRED OF INTERACTIONS, THEN

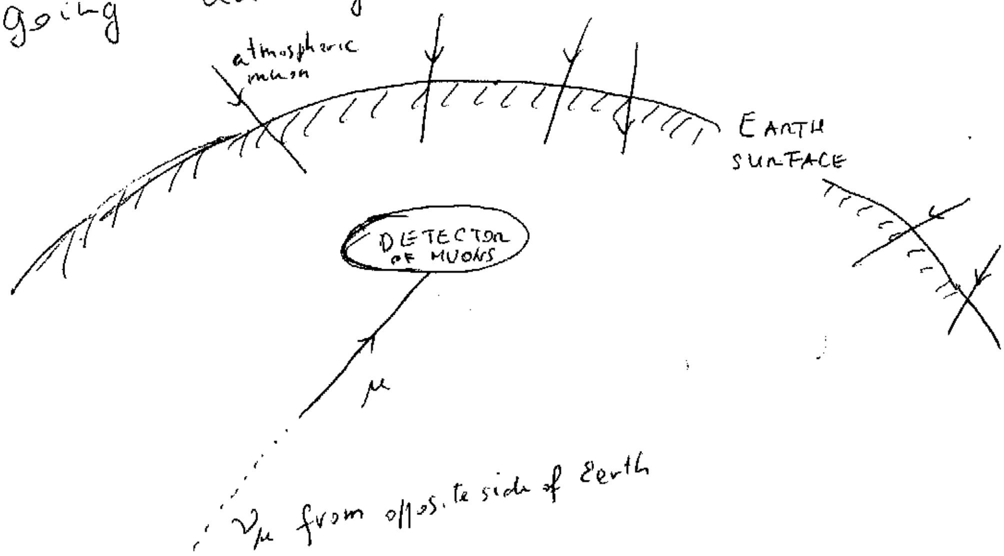
## SEEING $\overset{(-)}{\nu}_\mu$

The older method of detection of $\nu_\mu$ is through muons. Muons range is very roughly given by

$$R = 1\,\text{km w.e.} \times \log\left(1 + \frac{E_\mu}{500\,\text{GeV}}\right),$$

much longer than electron's range.

Thus a "small" detector can attempt the following: Use the Earth as a $\nu_\mu - \mu$ converter; shield $\mu^\pm$ from cosmic ray going underground.




MUONS COMING FROM BELOW <u>CANNOT</u> BE OF COSMIC ORIGIN, MUST BE $\overset{(-)}{\nu}_\mu$ CONVERTED INTO $\mu^\pm$.

This method suggested by Markov and Greisen in 1960 is still used to try high energy neutrino astronomy (Stanev lectures)

## FERMI LAGRANGIAN

$$\mathcal{L}_{Fermi} = -\frac{G_F}{\sqrt{2}}\left(\overline{J}^{\mu}_{hadr} + \overline{J}^{\mu}_{lept}\right)\cdot\left(J_{\mu\,hadr} + J^{\mu}_{lept}\right)$$

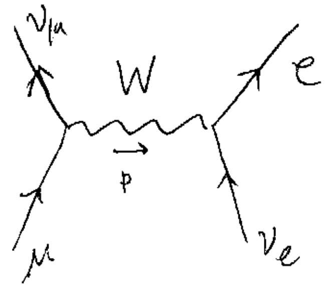
This Lagrangian regulates all low energy processes involving neutrinos (decays & interact. rates)

$$J_{\mu}^{(hadr)} = \overline{u}_i \gamma_\mu (1-\gamma_5) V_{ij}\, d_j$$

$$J_{\mu}^{(lept)} = \overline{\nu}_i \gamma_\mu (1-\gamma_5)\, \delta_{ij}\, \ell_j$$

(This is not a fundamental term!)

## ORIGIN IN THE SM OF FERMI LAGRANGIAN




$$\simeq \frac{ig}{\sqrt{2}}\, \overline{u}_{\nu_\mu} \gamma^a P_L u_\mu \cdot \frac{-i g_{ab}}{p^2 - M_W^2} \cdot \overline{u}_e \gamma^b P_L u_{\nu_e} \frac{ig}{\sqrt{2}}$$

IN THE LIMIT $p^2 \ll M_W^2$, THE W-PROPAGATOR FURTHER APPROXIMATED TO A CONSTANT

$$-\frac{i g^2}{2 M_W^2}\, \overline{u}_{\nu_\mu} \gamma^a P_L u_\mu \cdot \overline{u}_e \gamma_a P_L u_{\nu_e}$$

WHICH DERIVES FROM

$$\mathcal{L}_{Fermi} = -\frac{4 G_F}{\sqrt{2}}\, \overline{\nu}_\mu \gamma^a P_L \mu \cdot \overline{e} \gamma_a P_L \nu_e$$

IF WE SET:

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 M_W^2}$$

NOTE THAT THE SIGN IS PREDICTED.

EXERCISE

(1) DERIVE THE EXPRESSION OF $M_W$ (BY CALCULATING $|\mathcal{D}_\mu \varphi|^2$ SETTING $\varphi \to \langle\varphi\rangle = v = 174\ \text{GeV}$)

(2) FIND THE EXPRESSION OF $G_F$ IN TERMS OF $v$.

# REMARKS ON (V−A) STRUCTURE

## E.M. (vector) INTERACTIONS CONSERVE P, C.

$$S_{int} = \int d^4x \; q \cdot A_\mu(x) \cdot J^\mu_{em}(x)$$

$$\begin{cases} A_0(x) \xrightarrow{P} A_0(x_P) \\ \vec{A}(x) \xrightarrow{P} -\vec{A}(x_P) \end{cases} \qquad \text{where } x_P = (x^0, -\vec{x})$$

By declaring $e(x) \xrightarrow{P} \gamma^0 e(x_P)$

$$\begin{cases} \rho(x) = \bar{e}(x)\gamma_0 e(x) \xrightarrow{P} \rho(x_P) \\ (\vec{J}(x))^i = \bar{e}(x)\gamma^i e(x) \xrightarrow{P} -(\vec{J}(x_P))^i \end{cases}$$

Thus,

$$S_{int} \xrightarrow{P} \int d^4x \; q \; A_\mu(x_P) \cdot J^\mu_{em}(x_P) = \int d^4x_P \, q \, A_\mu(x_P) J^\mu_{em}(x_P).$$

The trouble with weak interactions is that there are VECTOR and AXIAL components of the current at the same time; they transform with opposite signs!

$$\frac{g}{\sqrt{2}} W^+_\mu(x) \bar{\nu}_e(x) \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) e(x) \xrightarrow{P} \frac{g}{\sqrt{2}} W^+_\mu(x_P) \overline{\nu_e(x_P)} \gamma^\mu \left(\frac{1+\gamma_5}{2}\right) e(x_P)$$

CC (V−A) interactions violate P (and C) maximally

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EXERCISE Show that the same happens with C, where we need to define $\psi \xrightarrow{C} C\bar{\psi}^t$.

According to early Fermi proposal, the interaction were modeled on e.m.: $\bar{n}\gamma^\mu p \cdot \bar{\nu}\gamma_\mu e$ which again conserves parity. It took many years to reach full understanding of V−A structure

This causes several observable phenomena e.g., correlations between spin and momenta. [For instance, the electron produced in $\mu$ decay is preferentially emitted in the direction of $\mu$-polarization]

The modern view ~~of~~ this structure of weak interaction is a bit different:

$\bar{\nu}_L \gamma^\mu e_L$

does not ~~even~~ contain $\nu_R$. Thus, parity maps this terms into a NON-EXISTING interaction term. – i.e., parity is violated.

This argument resembles the old one, that the V-A structure ~~[illegible] a link with~~ suggests ~~that~~ an explanation why $\nu$ masses are so small. Consider the Dirac free Lagrangian:

$$\mathcal{L}_0 = i\bar{\psi}\left(\hat{\partial} - m\right)\psi = i\left(\bar{\psi}_L \hat{\partial} \psi_L + \bar{\psi}_R \hat{\partial} \psi_R\right) - m\left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L\right)$$

If $\psi_R$ ~~is forbidden~~ is excluded, it is not possible to form a Dirac mass term. (We will make this connection completely clear later)

## FIRST DISCUSSION OF $\nu$ MASSES [illegible]

THE BEHAVIOUR OF THE ELECTRON DISTRIBUTION IN $\beta$ - DECAY $\left( (A,Z) \to (A,Z+1) + e^- + \bar{\nu}_e \right)$ IS DICTATED SIMPLY BY $\bar{\nu}_e$ PHASE SPACE AT THE "ENDPOINT", I.E., MAXIMUM $e^-$ - ENERGY;

IN FACT $Q = E_e + E_{\bar{\nu}_e} \Rightarrow \left( E_e^{max} \Leftrightarrow E_{\bar{\nu}_e}^{min} \right)$

$$d^3 p_\nu = d\Omega_\nu \, p_\nu E_\nu dE_\nu = d\Omega_\nu \sqrt{(Q-E_e)^2 - m_\nu^2} \cdot (Q-E_e) \cdot dE_e$$

IF ONE BELIEVES THAT $\bar{\nu}_e$ IS A SUPERPOSITION OF VARIOUS MASS STATES, THAT ARE NOT DETECTED INDIVIDUALLY, ONE HAS TO SUM THE PROBABILITIES:

$$\Gamma_{(\bar{\nu}_e)} = \sum_i \Gamma(\bar{\nu}_i) \propto d^3 p_{\nu i} \propto (Q-E_e)\sqrt{(Q-E_e)^2 - m_i^2} \, |U_{ei}^2| \, dE_e$$

WHERE WE DECLARE THAT $\bar{\nu}_e \equiv \sum_{i=1}^{N} U_{ei} \cdot \bar{\nu}_i$.

These searches, conducted since 30'-ies, are now pushed to the limit of 2 eV; in the future, the plan is to probe masses as small as 0.2 eV.

<u>EXERCISE</u>: (1) SUPPOSE THAT THE ENERGY $E_e$ IS MEASURED VERY PRECISELY; PLOT THE SHAPE OF $\beta$ SPECTRUM AT END POINT.

(2) SUPPOSE (MORE REALISTICALLY) THAT $E_e$ IS MEASURED WITH A "LARGE" EXPERIMENTAL ERROR; SHOW THAT THE EFFECTIVE SPECTRUM RESEMBLES THE ONE OF A SINGLE $\bar{\nu}_e$

**A Common DEFINITION of neutrinos**

'Electron' (muon, tau) neutrinos is <u>the neutral particle that accompanies</u> the corresponding charged particle in week interactions.
The <u># of electrons + electron neutrinos</u> (similarly for $\mu$ and $\tau$) <u>is conserved</u>.

Examples:

(1) $\pi^+ \to \mu^+ \nu_\mu$
This is a $\mu$-neutrino. [In fact, $\varnothing$ $\mu$ in initial state, $1\ \mu^+$ in final state, must be $\nu_\mu$]

(2) $n \to p\, e^- \bar{\nu}_e$
This is an <u>anti</u> electron neutrino. [Can be seen by $\bar{\nu}_e p \to e^+ n$.]

(3) $\mu^- \to \nu_\mu e^- \bar{\nu}_e$
These are a muon neutrino and an electron anti-neutrino.

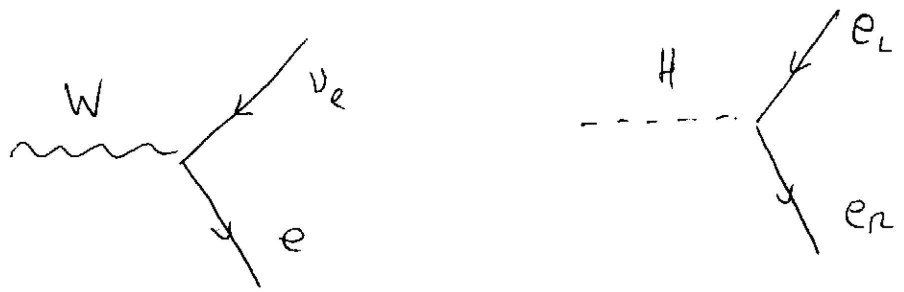
[THIS, IN FACT, ASSUMES $\boxed{\text{LEPTON NUMBER}}$ CONSERVATION, AS SUGGESTED, E.G., BY ABSENCE (RARITY) OF $\mu \to e\gamma$, $\mu^- \to e^- e^- e^+$, etc
ALSO TAKES INTO ACCOUNT THAT $\nu_\mu$ FROM $\pi^+$ MAKE $\mu^-$; $\bar{\nu}_e$'s FROM $\beta$ DECAY MAKE $e^+$, etc]

# HOW LEPTON # CONSERVATION ARISES IN SM

$$\mathcal{L}_{SM} \ni i\, \bar{l}_{eL} \hat{D}\, l_{eL}, \quad i\, \bar{e}_R \hat{D}\, e_R, \quad H\, \bar{l}_{eL}\, e_R$$

IF $l_{eL} \to e^{i\alpha} l_{eL}$, $e_R \to e^{i\alpha} e_R$, THE LAGRANGIAN IS UNCHANGED.

DIAGRAMMATICALLY, THE FERMION ARROWS ARE CONCORDANT, e.g.




etc

THERE ARE 4 SUCH SYMMETRIES IN SM

$$L_e, \quad L_\mu, \quad L_\tau, \quad B$$

NAMELY THE 3 lepton # and THE BARYON NUMBER.

Why there are not 3 seperate baryon numbers? This has been explained by Silvestrini:

$$\mathcal{L}_{CC} \ni \frac{g}{\sqrt{2}}\, W^+_\mu \sum_{i,j=1,2,3} \bar{u}_{iL}\, \gamma^\mu\, V^{(CKM)}_{ij}\, d_{jL}$$

It should be noted that these global symmetries are not IMPOSED BY HAND rather, they come as a little surprise, ~~they~~ after writing the most general lagrangian compatible with $SU(3)_c \times SU(2)_L \times U(1)_Y$ and given particle content.

They are called <u>ACCIDENTAL SYMMETRIES</u>.

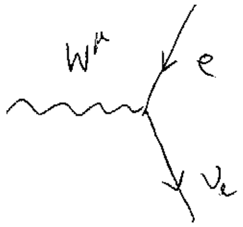
More precisely:

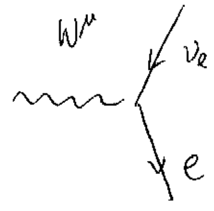
$$i\,\bar{l}_L \hat{D}\, l_L = i\left(\bar{\nu}_e, \bar{e}\right)\left[\hat{\partial} - \frac{i}{2}\begin{pmatrix} gA_3 - g'\hat{B}, & g(A_1 - iA_2) \\ g(A_1 + iA_2) & -gA_3 - g'B \end{pmatrix}\right]\begin{pmatrix} \nu_e \\ e \end{pmatrix}$$

$$\ni \frac{g}{\sqrt{2}}\left(W^+_\mu\, \bar{\nu}_{e_L} \gamma^\mu e_L + W^-_\mu\, \bar{e}_L \gamma^\mu \nu_{eL}\right)$$

where

$$\begin{cases} \hat{x} = x_\mu \cdot \gamma^\mu & (\text{my convention for the "slash"}) \\ W^\pm = \dfrac{A_1 \mp i A_2}{\sqrt{2}} \end{cases}$$

Thus: 

$i\frac{g}{\sqrt{2}}\gamma^\mu P_L$ 

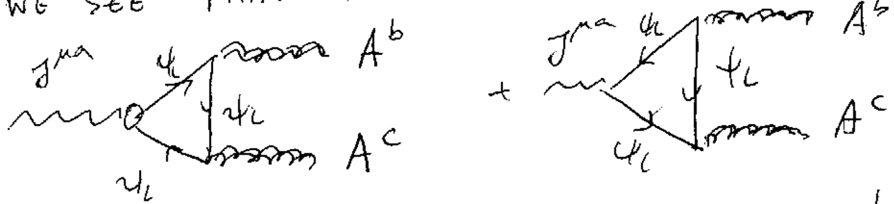
$i\frac{g}{\sqrt{2}}\gamma^\mu P_L$

## ANOMALIES (i.e., unexpected violation of symm. due to QFT)

VECTOR CURRENTS ARE CONSERVED ALSO IN QUANTUM F.T BUT AXIAL CURRENTS ARE NOT. DEFINING $J_L^{\mu a} = \bar{\psi}_L \gamma^\mu t^a \psi_L$

$$\partial_\mu J_L^{\mu a} = \frac{1}{4} \frac{g^2}{(4\pi)^2} \epsilon^{\alpha\beta\gamma\delta} F^b_{\alpha\beta} F^c_{\gamma\delta} \, \mathrm{tr}\left[t^a \{t^b t^c\}\right]$$

WHERE WE SEE THAT THE CTRB COMES FROM GAUGE BOSONS:




EXERCISE From conservation of vector current, obtain the divergence of $J_R^{\mu a}$.

IN THE SM, THE GAUGE COUPLINGS ARE CHIRAL, SO ONE COULD WORRY THAT A NON-ZERO RESULTS SPOILS GAUGE INVARIANCE. BUT $\mathrm{tr}[t^a\{t^b t^c\}]$ TURNS OUT TO BE ZERO FOR ALL CURRENTS: LOCAL SYMM. ARE SAFE

THE SITUATION IS DIFFERENT FOR GLOBAL SYMM.

$$J_B^\mu = \frac{1}{3}\left[\bar{q}_L \gamma^\mu q_L + \bar{u}_R \gamma^\mu u_R + \bar{d}_R \gamma^\mu d_R\right]$$

$$J_{L_e}^\mu = \bar{l}_{eL} \gamma^\mu l_{eL} + \bar{e}_R \gamma^\mu e_R$$

etc.

WHILE THE "ANOMALIES" DUE TO $\gamma$ & $G$ ARE CANCELED (no surprise: the couplings are vectorial) THOSE DUE TO $W^+ W^-$ RADIATION ARE NOT, SINCE THESE COUPLE ONLY TO LEFT FIELDS.

IT ~~REMAINS THEN~~ HAPPENS SO, HOWEVER, THAT $J_B^\mu - (J^\mu_{L_1} + J^\mu_{L_2} + J^\mu_{L_3})$ AND $J^\mu_{L_i} - J^\mu_{L_j}$ ARE ANOMALY FREE. THIS MEANS THEY REMAIN GOOD SYMM. ALSO IN QFT CONTEXT.