Aspects of 3-3-1 models

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Outline

1. Introduction: 3-3-1 models
2. Type of 3-3-1 models
3. The Landau pole in 3-3-1 models
4. Phenomenology:proposals
5. Conclusions

3-3-1 MODELS:

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

$$\downarrow$$

$$SU(3)_C \otimes SU(3)_L \otimes U(1)_X$$

+ REPRESENTATION CONTENT

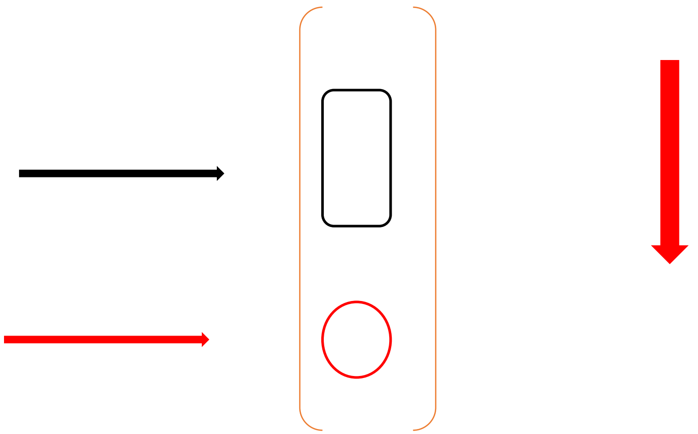
$3, 3^*, 6, 10, \ldots$

(anti)triplet of SU(3): 3=2 ⊕ 1

SU(3)

(anti)DUBLETO DE SU(2)

SINGLET OF SU(2)



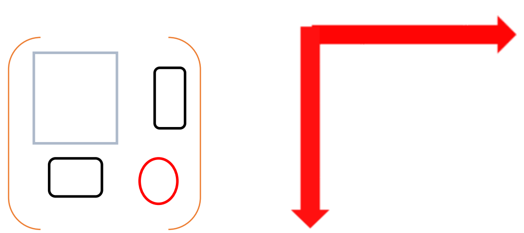
SU(3):

6=1 ⊕ 2 ⊕ 3

SU(3)

TRIPLET OF SU(2)

$6 =$



3-3-1 MODELS

ELECTRIC CHARGE OPERATOR

3 $$Q_{\alpha\beta}(X) = \ (\lambda_3\,\alpha + \lambda_8\,\beta + X)$$ Hereafter α=1

3* $$\bar{Q}_{\alpha\beta}(X) = \ (-\lambda_3\,\alpha - \lambda_8\,\beta + \ \bar{X})$$

★ $$Q_{-\sqrt{3}}(\mathrm{X}) = \begin{pmatrix} X & 0 & 0 \\ 0 & -1+X & 0 \\ 0 & 0 & 1+X \end{pmatrix}$$

$$Q_{\sqrt{3}}(\mathrm{X}) = \begin{pmatrix} 1+X & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1+X \end{pmatrix}$$

$$Q_{-1/\sqrt{3}}(\mathrm{X}) = \begin{pmatrix} \frac{1}{3}+X & 0 & 0 \\ 0 & -\frac{2}{3}+X & 0 \\ 0 & 0 & \frac{1}{3}+X \end{pmatrix}$$

$$Q_{1/\sqrt{3}}(\mathrm{X}) = \begin{pmatrix} \frac{2}{3}+X & 0 & 0 \\ 0 & -\frac{1}{3}+X & 0 \\ 0 & 0 & -\frac{1}{3}+X \end{pmatrix}$$

MODELS, IN GENERAL, HAVE TWO INGREDIENTS

1. GAUGE SYMMETRY
2. PARTICLE CONTENT (DEGREES OF FREEDOM)

Although the 3-3-1 models can be classified by the β parameter in the electric charge operator Q, this is not enough to distinguishes all the models: the particle content, matter. Models with the same β have different phenomenology

We will consider below two examples, two with $\beta = -\sqrt{3}$ and two with $\beta = -1/\sqrt{3}$.

$\beta = -\sqrt{3}$

The minimal 3-3-1 model (m331)

$$\Psi_l = (\nu_l \; l \; l^c)_L^T \sim (1, 3, 0), \qquad l = e, \mu, \tau$$

only the known leptons

$$Q_m = (d_m, -u_m, j_m)_L^T \sim \left(3, 3^*, \frac{2}{3}\right); m = 1,2$$

$$Q_3 = (u_3, d_3, J)_L^T \sim \left(3, 3, \frac{2}{3}\right)$$

$$u_{\alpha R} \sim \left(3, 1, \frac{2}{3}\right), \quad d_{\alpha R} \sim (3, 1, -\frac{1}{3}) \quad J_R \sim \left(3, 1, \frac{5}{3}\right), j_{mR} \sim (3, 1, -\frac{4}{3})$$

Scalar sector:

$$\eta = \begin{pmatrix} \eta^0 \\ \eta^-{}_1 \\ \eta^+{}_2 \end{pmatrix} \sim(3,0), \quad \rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^{++} \end{pmatrix} \sim(3,+1), \quad \chi = \begin{pmatrix} \chi^- \\ \chi^{--} \\ \chi^0 \end{pmatrix} \sim(3,-1)$$

$$SU(3)_C \otimes SU(3)_L \otimes U(1)_X \xrightarrow[v_\chi]{} SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \xrightarrow[v_\eta, v_\rho, v_s]{} SU(3)_C \otimes U(1)_Q$$

The VEVs of η,ρ and χ are enough to break the symmetries espontaneously and giving at the same time the quark masses. But no for leptons. For the later ones it is necessary to add

The sextet:

$$S = \begin{pmatrix} T & D \\ D^T & H^{--} \end{pmatrix} \sim(6,0)$$

Under SU(2): doublet, triplet, and singlet

$$D = \begin{bmatrix} s^+ \\ s^0 \end{bmatrix}, \quad T = \begin{pmatrix} t^0 & t^+ \\ t^+ & t^{++} \end{pmatrix}, \quad H^{--}$$

Several options for neutrino mass generation

Leptons in the minimal 331 model

$$\psi = \begin{pmatrix} \nu_{eL} \\ l_L \\ l_L^c \end{pmatrix} \sim (3,0) \quad \nu_{lR} \sim (1,0)$$ Optional as in the SM

NEUTRAL CURRENTS: $g_V^{\nu}, g_A^{\nu}, g_V^{e}, g_A^{e}$ with Z

$f_V^{\nu}, f_A^{\nu}, f_V^{e}, f_A^{e}$ with Z'

There is Lepton number violation

OTHE MODEL WITH $\beta = -\sqrt{3}$

331HL (ONE HEAVY LEPTON PER FAMILY)

$$\psi = \begin{pmatrix} \nu_{eL} \\ l_L \\ E_L^+ \end{pmatrix} \sim (3,0) \quad l_R \sim (1,-1), E_R \sim (1,+1)$$

$\nu_{lR} \sim (1,0)$ are again optional

Only the three scalar triplets $\eta \sim (3,0)$, $\rho \sim (3,+1)$, $\chi \sim (3,-1)$

NEUTRAL CURRENTS: $g_V^\nu, g_A^\nu, g_V^e, g_A^e, g_V^E, g_A^E$ with Z

$f_V^\nu, f_A^\nu, f_V^e, f_A^e, f_V^E, f_A^E$ with Z'

Then in models with $\beta = -\sqrt{3}$ and heavy leptons

1. Lepton number is not violated if the heavy leptons E´s are particles not anti-particles (Konopinski-Mahmoud scheme)

2. The heavy leptons, E's, do not mix with the known leptons e,μ,τ, they may be stable because an acidental Z_2 symmetry unless interactions in the scalar sector allow them to decay into the known leptons.

In fact, the term $a_{10}(\chi^+\eta)(\rho^+\eta)$ in the escalar potential breaks the Z_2 symmetry alowing the decay $E \rightarrow l + \nu + \nu$

MODELS WITH $\beta = -1/\sqrt{3}$

$$\psi = \begin{pmatrix} \nu_{eL} \\ l_L \\ \nu_L^c \end{pmatrix} \sim (3,-1),\ l_R \sim (1,-1)$$

NEUTRAL CURRENTS: $g_V^\nu, g_A^\nu, g_V^e, g_A^e$ with Z

$f_V^\nu, f_A^\nu, f_V^e, f_A^e$ with Z'

AS IN THE m331 MODEL, THERE IS THE LEPTON NUMBER VIOLATION

The neutral férmions (neutrinos) mass matrix is 6x6 or

$$\psi = \begin{pmatrix} \nu_{eL} \\ l_L \\ N_L \end{pmatrix} \sim (3,\text{-}1),\ l_R \sim (1,\text{-}1),\ N_R \sim (1,0),\ \nu_R \sim (1,0)$$

NEUTRAL CURRENTS: $g_V^{\nu}, g_A^{\nu}, g_V^{e}, g_A^{e}, g_V^{N}, g_A^{N}$ with Z

$f_V^{\nu}, f_A^{\nu}, f_V^{e}, f_A^{e}, f_V^{N}, f_A^{N}$ with Z'

THE LEPTON NUMBER IS CONSERVED IF N ARE IS CONSIDER PARTICLES.
N MAY BE STABLE AND THE LIGHTEST ONE CAN BE CANDIDATE TO DARK MATTER

The neutral férmions mass matrix is 12x12

LANDAU POLE IN 3-3-1MODELS

Gauge couplings in 3-3-1 models:

$$g_s, g_{SU(3)} = g, g_X$$

DEFINING $\tan \theta_X = \frac{g_X}{g}$

e=g$\frac{s_X}{\sqrt{1+3s_X^2}}$ e=$g_X \frac{s_X}{\sqrt{1+3s_X^2}}$

Matching condition with the SM

$\beta=\pm\sqrt{3}$ (m331)

$$\frac{s_X^2}{1+3s_X^2} = s_W^2 \qquad \Rightarrow$$

$$tan^2\,\theta_X = \frac{s_W^2}{1-4s_W^2} \quad \Rightarrow \quad s_W^2 < 0.25$$

=0.25 at μ~4-8 TeV

$\beta=\pm 1/\sqrt{3}$

$$tan^2\,\theta_X = \frac{s_W^2}{1-\frac{4}{3}s_W^2} \quad \Rightarrow \quad s_W^2 < 0.75$$

It seems as if the existence of the pole is just due to the introduction of an angle that do not exist in the model.

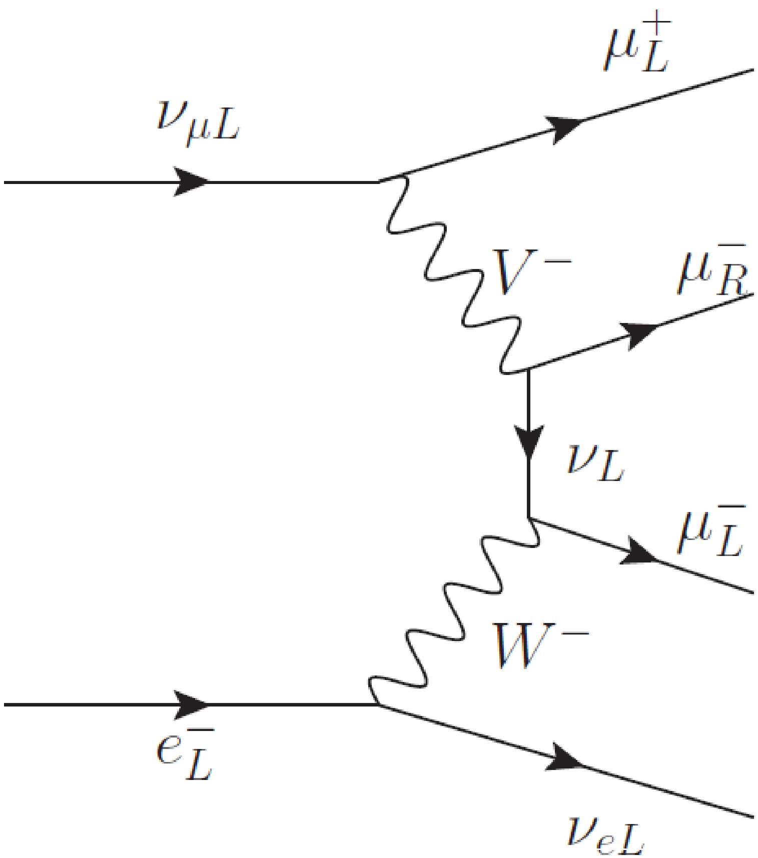
PHENOMENOLOGY: PROPOSALS

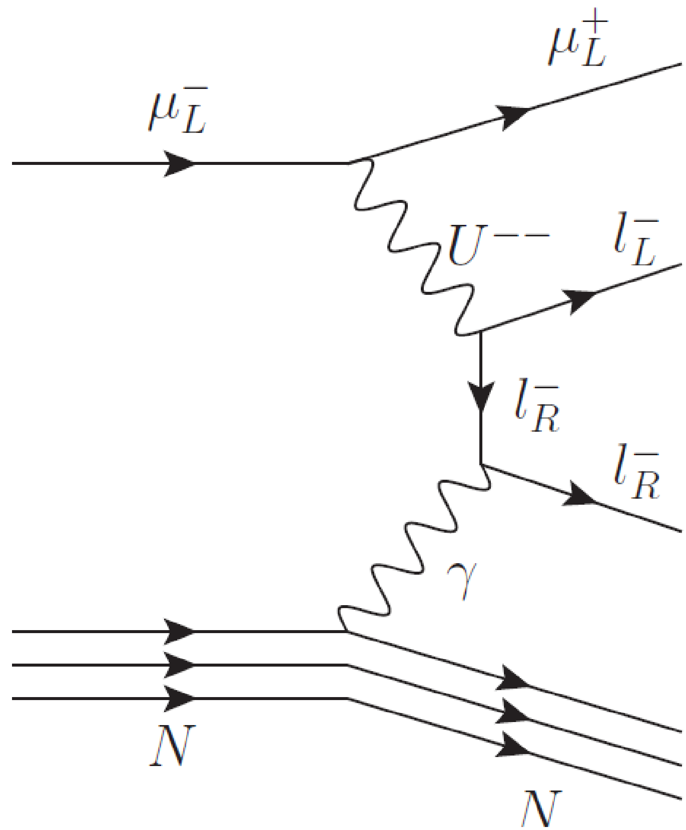
1. Better calculation of the Landau pole
   (lattice gauge theories)
2. Flavor physics, Z' but scalars has to
   be consider too
2. Low energy processes. For example Q~MeV-GeV
   νN scattering
3. Colliders phenomenology, see Cao and Zhang
   arXiv:1611.09337
4. High energy neutrino processes

TRILEPTON EVENTS

$$\nu_{\mu L} + e_L^- \rightarrow l_{1L}^- + l_{2L}^+ + l_{2R}^+ + \nu_{lL}$$

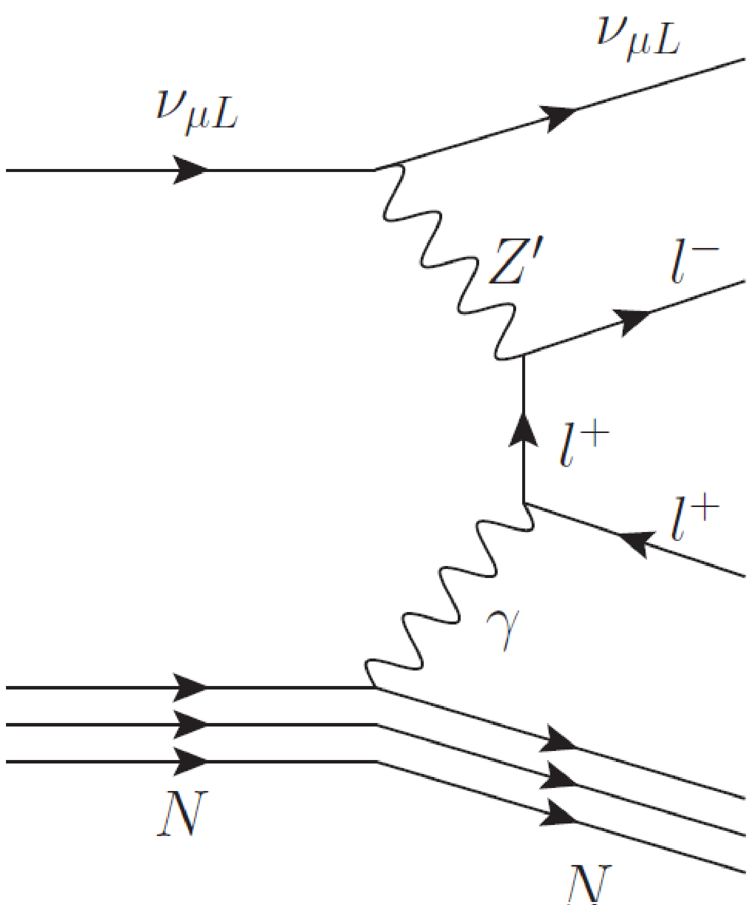
$$\mu_L + N \rightarrow l_{1L}^- + l_{2L}^+ + l_{2R}^+ + \mathrm{N}$$





TRIDENT NEUTRINO PRODUCTION

$$\nu_{\mu L} + N \rightarrow \nu_{\mu L} + l^{-} + l^{+} + N$$



PINGU AND ROCA EXPERIMENTS

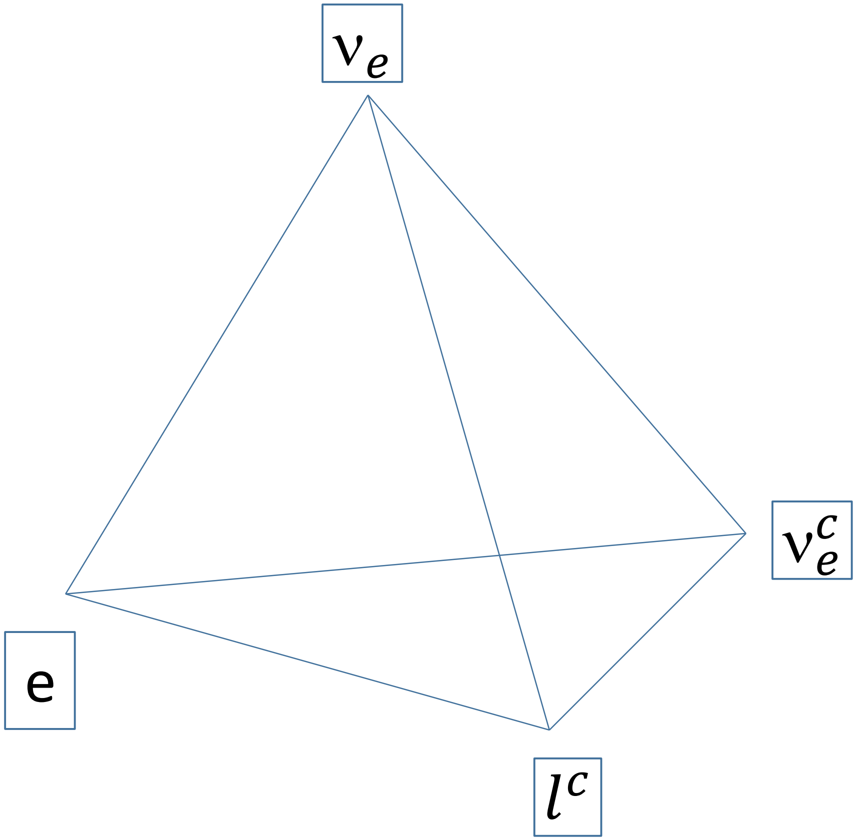
Ge et al arXiv:1702.02617

FINALLY

If right-handed neutrinos do really exist:
the electroweak symmetry may be

$$SU(4)_L \otimes U(1)_X$$

Pisano and Pleitez PRD 1994



CONCLUSIONS

1. 331 models are three families models

2. All models have Landau-like pole implying an upper bound on $s_W^2 (< 0.25)$ in some models
3. They give rationale for the multi-Higgs extensions of the SM
4. The electric charge is quantized independently of the neutrino masses (massless or massive Dirac or Majorana).
5. Many mechanism for netrino mass generation
6. They have an almost automatic Peccei-Quinn symmetry
7. They predict the existence of doubly charged vector bóson U_μ^{++} or complex neutral ones, X_μ^0.
8. Dark matter candidates
9. The models predict FCNC effects, in particular it can explains the anomaly in B_s decay (added after the presentation)

Some references

1. Machado et al Lepton flavor violating processes in the minimal 3-3-1 model with singlet sterile neutrinos, arXiv:1604.08539
2. Machado et al Flavor-changing neutral currents in the minimal 3-3-1 model revisited, Phys. Rev. D 88, 113002 (2013)
3. A. J. Buras et al 331 models Facing the tension in ΔF=2 processes with the impact on $\frac{\varepsilon'}{\varepsilon}$, $B_s \to \mu^+\mu^-, B \to K^*\mu^+\mu^-$, JHEP 1608 (2016) 115
4. A. J. Buras et al, $\frac{\varepsilon'}{\varepsilon}$ in 331 models, JHEP 1603 (2016) 010

and references therein

thanks!

Triangle anomalies (only the nontrivial ones)

1) $[SU(3)_C]^2 U(1)_X$: Tr($\{T_C^a, T_C^b\}$X)=0 Sum only over the quark degrees of freedom:

Tr($\{T_C^a, T_C^b\}$X)= $\delta^{ab} Tr\ X$=6($-\frac{1}{3}$)+3($\frac{2}{3}$)+3($\frac{2}{3}-\frac{1}{3}$)+$\frac{5}{3}+2\left(-\frac{4}{3}\right)=0$

2) $[SU(3)_C]^3$: Tr($\{T^a, T^b\}T^c$)=0

Since $T^a = -T^{a*}$ This trace cancel out if the number of triplets is equal to the number of antitriplets

3) $[SU(3)_L]^2 U(1)_X$: Tr($\{T^a, T^b\}$X)=0 sum is over all fermions in triplets

$$Tr\left(\{T^a, T^b\}X\right) = \delta^{ab} Tr\ X = 6\left(-\frac{1}{3}\right) + 3\left(\frac{2}{3}\right) + 3(0) = 0$$

4) $[U(1)]^3$: Tr($\{X, X\}$X)= Tr({X,X}X)=TrX_L^3 − TrX_R^3

$$=18\left(-\frac{1}{3}\right)^3 + 9\left(\frac{2}{3}\right)^3 - 3\left[3\left(\frac{2}{3}\right)^3 + 3\left(-\frac{1}{3}\right)^3 + \left(\frac{5}{3}\right)^3 + 2\left(-\frac{4}{3}\right)^3\right] = 0$$

Scalar sector in both:

$$\eta = \begin{pmatrix} \eta_1^0 \\ \eta^- \\ \eta^0{}_2 \end{pmatrix} \sim(3,-1/3),\ \rho = \begin{pmatrix} \rho_1^+ \\ \rho^0 \\ \rho_2^+ \end{pmatrix} \sim(3,+2/3),\ \chi = \begin{pmatrix} \chi_1^0 \\ \chi^- \\ \chi_2^0 \end{pmatrix} \sim(3,-1/3)$$

Depending of the model ν^c or N in the third components, the vacuum aligment may be Different and also a sextet coul be added.

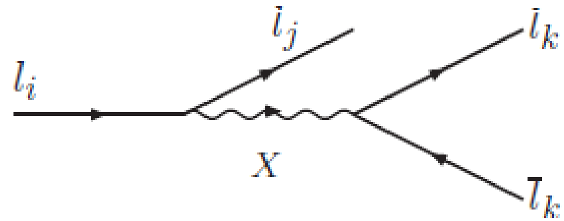
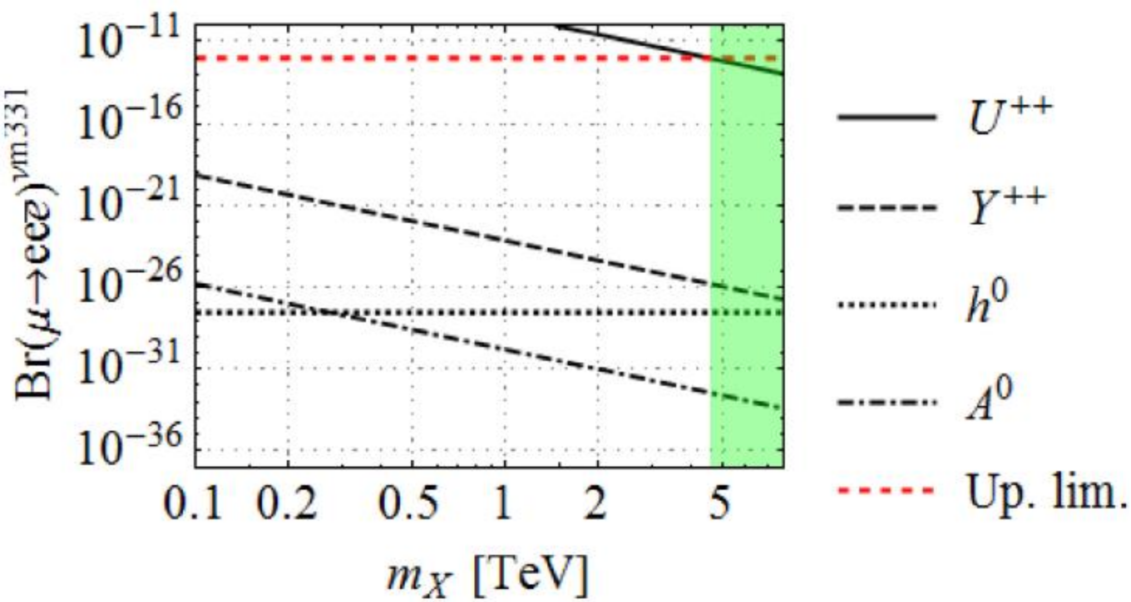
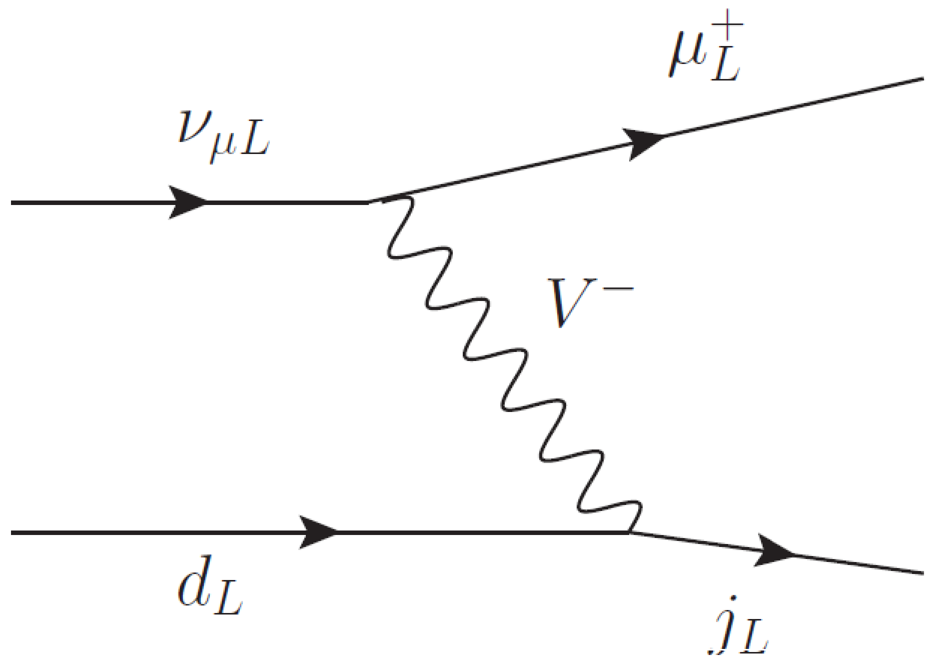


FIG. 2: Decay $l_i \to l_j l_k \bar{l}_k$ due to the virtual particles $X \equiv U_\mu^{++}, Y^{++}, h^0$, and A^0.



$$\nu_{lL} + N \rightarrow \mu_L^+ + X_j^-(jud)$$



THE STANDARD MODEL

FERMIONS

(three generations)

$\begin{pmatrix} \nu_l \\ l \end{pmatrix}_L \quad l_R$

No right-handed (sterile) neutrinos

9 degrees of freedom

$\begin{pmatrix} u \\ d \end{pmatrix}_L \rightarrow \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{matrix} u_R \rightarrow u_R \quad u_R \quad u_R \\ d_R \rightarrow d_R \quad d_R \quad d_R \end{matrix}$

36 degrees of freedom

BOSONS

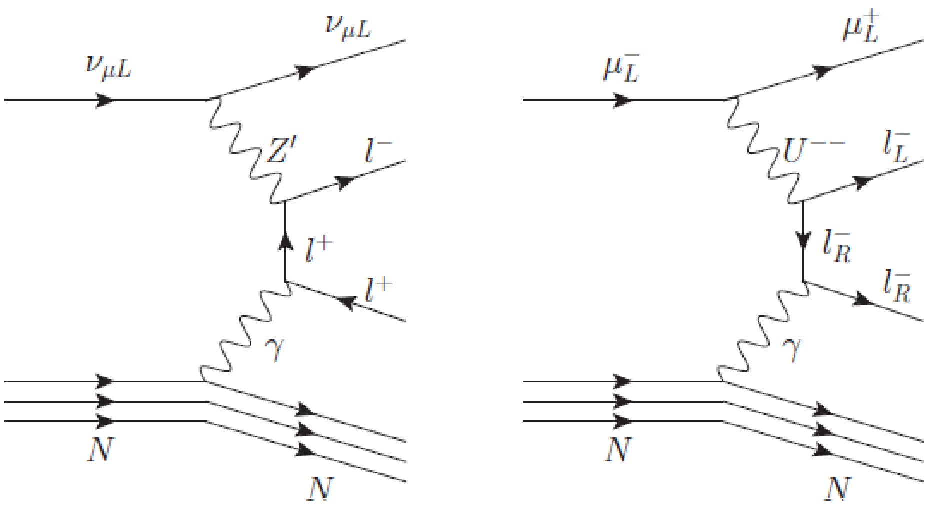
GAUGE: $\Upsilon, W^{\pm}, Z^0, G^a, a = 1, \ldots 8$ HIGGS: H^0

12 degrees of freedom

TOTAL 57 degrees of freedom

ALL THESE PARTICLES AND ITS PROPERTIES HAVE BEEN OBSERVED AND MEASURED IN LABORATORY (FERMILAB,LEP,LHC,...)

$$\overset{(-)}{\nu}_\ell + N \to \overset{(-)}{\nu}_\ell + X, \quad (g) \quad \overset{(-)}{\nu} + N \to \mu^\pm + X, \quad (h)$$



(a) (b)

$$\nu_{lL}^{(C)} + N \rightarrow l_{1L}^{-} + l_{2L}^{+} + l_{2R}^{+} + \text{hadrons}$$

$$\nu_{\mu L} + N \rightarrow l_{1L}^{-} + l_{2L}^{+} + l_{2R}^{+} + \nu_{lL}$$

MODELS WITH THE SAME GAUGE SYMMETRY BUT DIFFERENT REPRESENTATION CONTENT HAVE TO BE CONSIDRED DIFFERENT BECAUSE THEY HAVE DIFFERENT PHENOMENOLOGY

IN THE CASE OF 3-3-1 MODELS THERE IS A PARAMETER β WHICH DISTINGUISH THE MODELS. HOWEVER, EVEN MODELS WITH THE SAME β CAN HAVE DIFFERENT REPRESENTATION CONTENT AND THUS, DIFFERENT PHENOMENOLOGY.

THE STANDARD MODEL

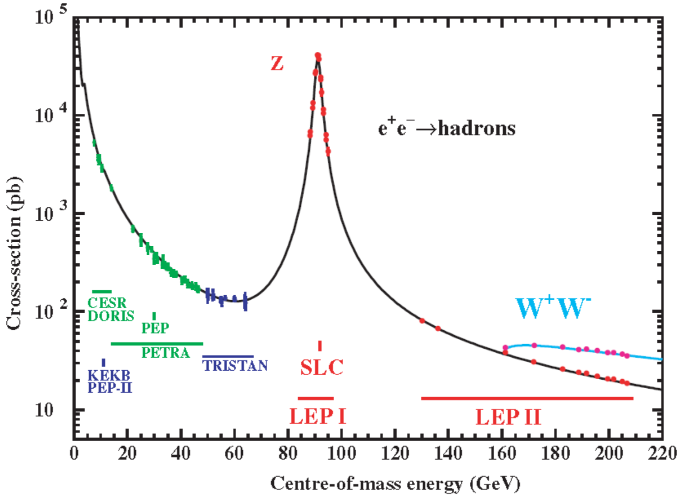
LEP:LEP+SLD COLL. Phys. Rept. **427,** 257 (2006) hep-ex/0509008

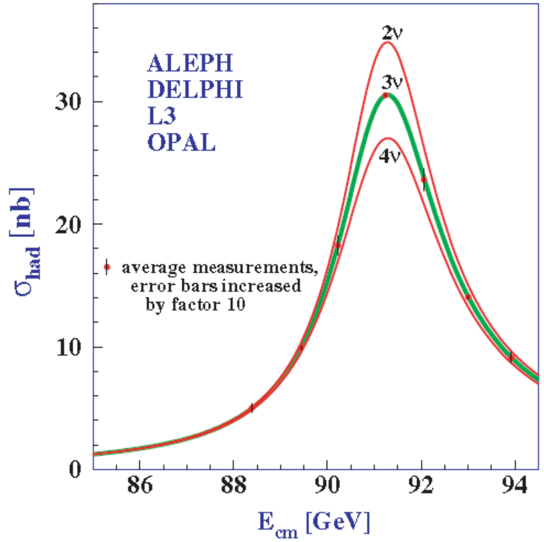
$M_Z = 91.1875 \pm 0.0021$ GeV

Γ_Z=2.4952±0.0023 GeV

$\rho_l = 1.0050 \pm 0.0010$

$sin^2{}_{eff} = 0.23153 \pm 0.00016$



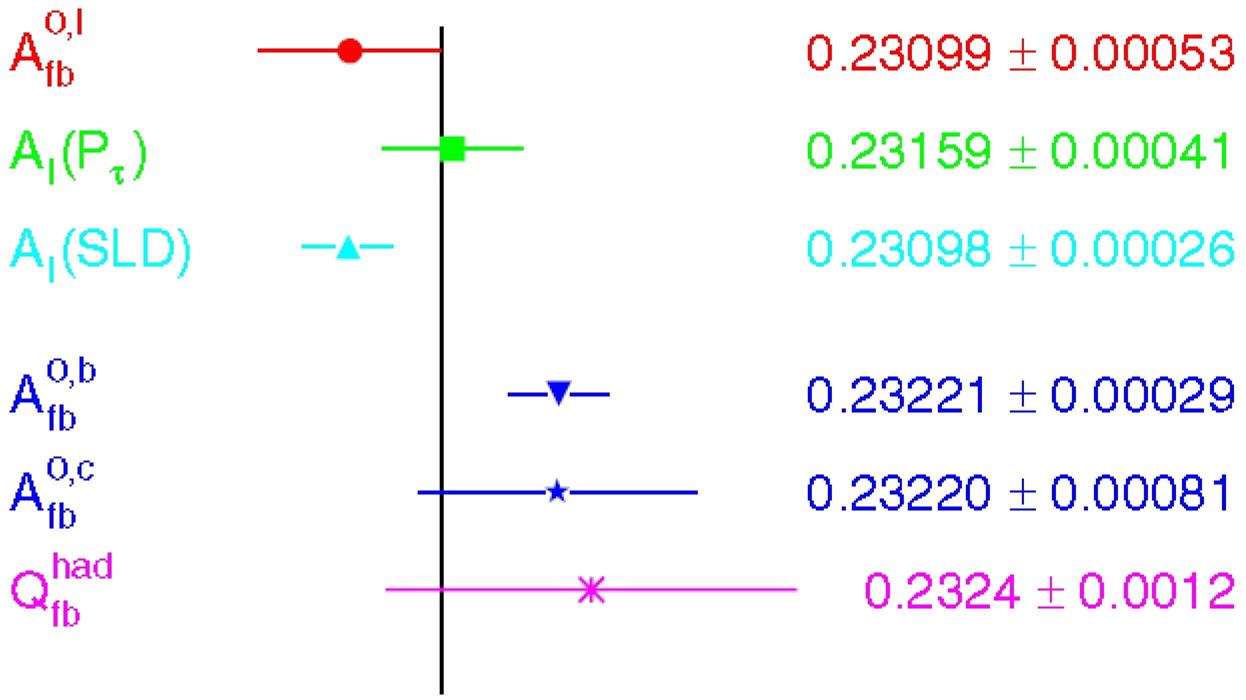


only three sequential generations

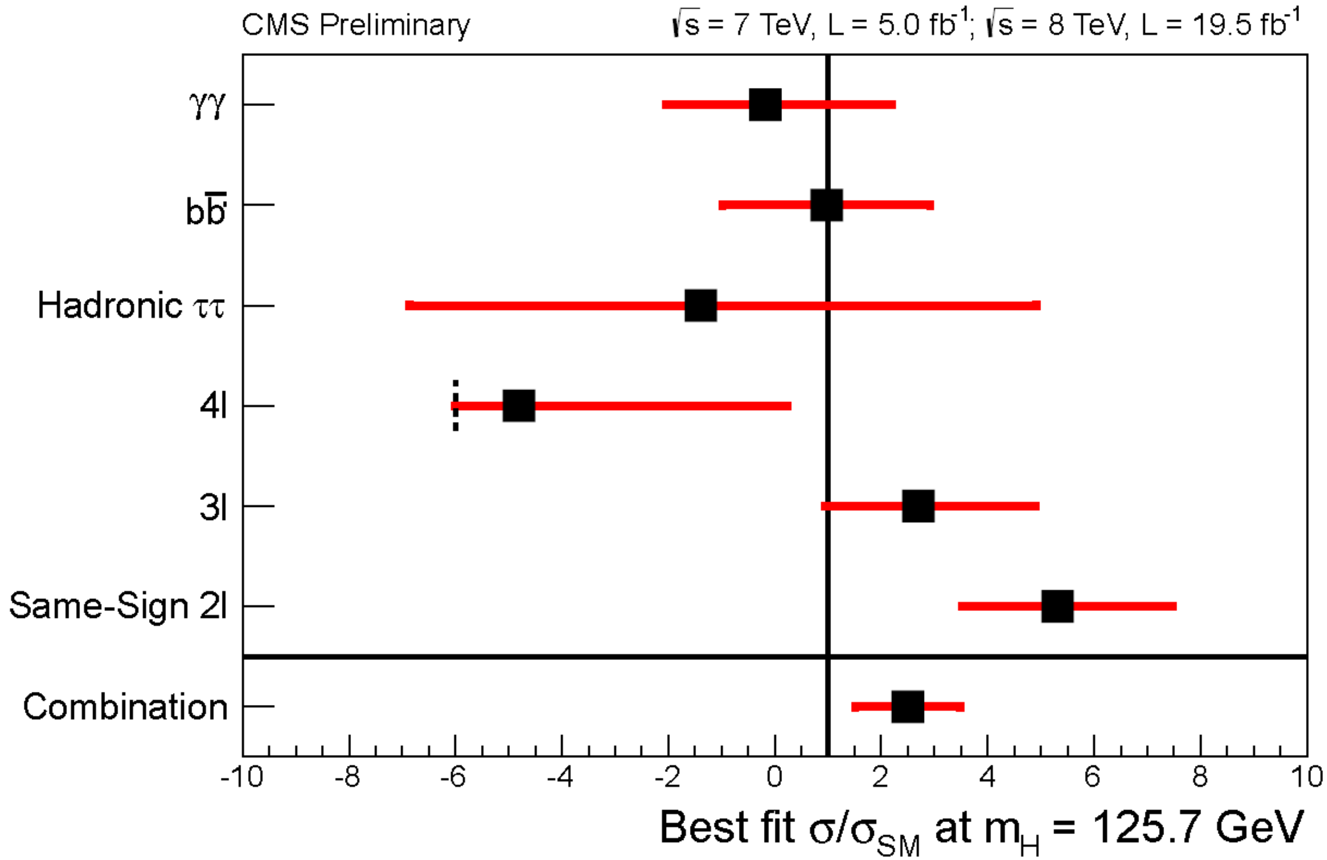
$$R_{inv} \equiv \frac{\Gamma_{\rm inv}}{\Gamma_{\ell\ell}} = N_\nu \left(\frac{\Gamma_{\nu\bar\nu}}{\Gamma_{\ell\ell}}\right)_{SM}.$$

$$N_\nu = 2.9840 \pm 0.0082,$$

THE STANDARD MODEL



THE STANDARD MODEL



However, only fairly weak limits were obtained on Higgs couplings to fermions of the first and third families. For instance $B(h^0 \to \mu\overline{\tau})$<8.2 x 10^{-3}. Roughly we can say that the ressonance with mass of around 125 GeV is in agreement with the SM Higgs bosons whithin the 20%.

Why Physics Beyond the SM?

Experiments/Astronomical Observations

- Neutrinos have mass and change flavor
- The nature of dark matter
- The muon anomaly a_μ differ 3.6 σ from the SM prediction
- Why CP violation is so small in strong interactions? $\theta \sim 10^{-9}$

Open questions in the SM

- Why are there only three (sequential) generations?
- Why is the electric charge quantized?
- Why $\sin\theta_W{}^2 \sim 0.25$

.... open questions in the SM

- Why $\frac{m_h}{m_{planck}} \sim 10^{17}$? (the hierarchy problem)
- Absence of couplings unification

•• The SM has about 20 free parameters, why? Who order them?

• • What determine the observed mass differences? and what fixes the mixing ? (The flavour problem)

•• $\frac{\Lambda_{vacuum}}{m_{Planck}} \sim 10^{120}$

(The cosmological constant problem)

OTHERS ....

MODEL BUILDING:

- GLOBAL AND LOCAL SYMMETRIES (DISCRET OR CONTINUOS)
- REPRESENTATION CONTENT (DEGREES OF FREEDOM)

DEGREES OF FREEDOM:

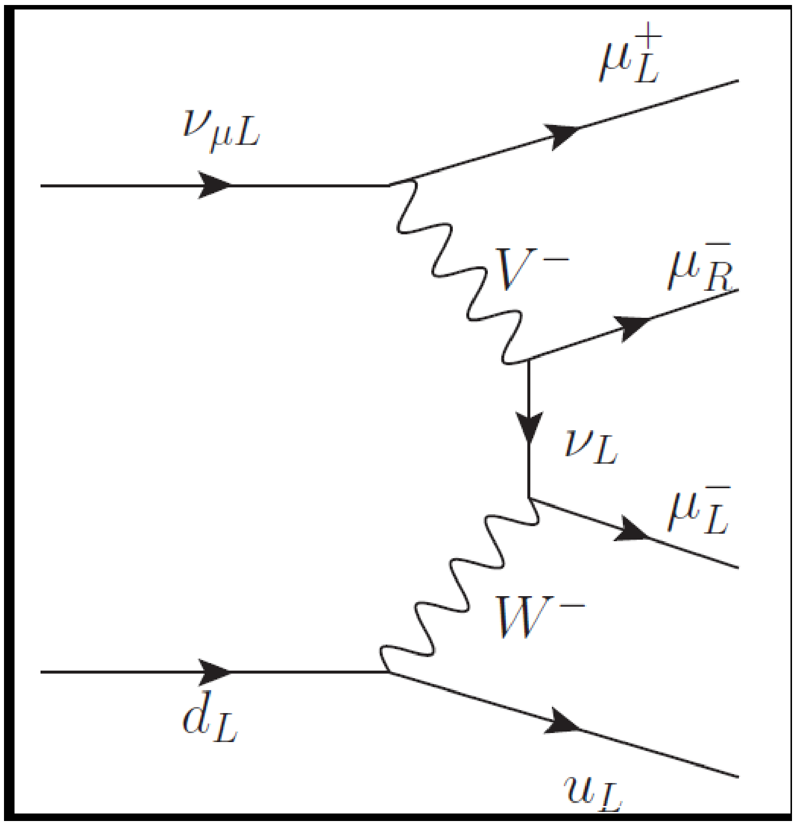
- VECTOR FIELDS: fixed by the gauge symmetries (adjoint representation)
- FERMION FIELDS: arbitrary (singlets or in higher representations)
- BOSON FIELDS: arbitrary (active or inert, singlets or in higher represenations)

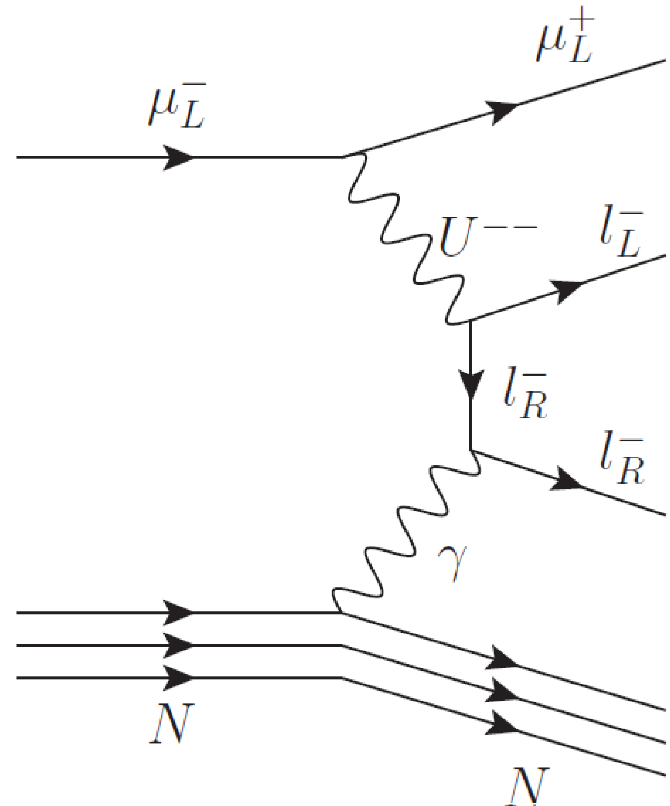
ALL THESE FIELDS CAN HAVE ANY VALUE FOR THE ELECTRIC CHARGE, LEPTON NUMBER,...

For a given symmetry we can add extra particles to the minimal number needed in the model to explain all the already observed or new effects.
However, the extra particles must to have potential explanation power.

$$\nu_{lL}^{(C)} + N \rightarrow l_{1L}^{-} + l_{2L}^{+} + l_{2R}^{+} + \text{hadrons}$$

TRILEPTON EVENTS





SOME ANSWER COME FROM 3-3-1 MODELS

- Why are there only three (sequential) generations? Because the representation content is free of anomalies if and only if there are a multiple of three generations. Asymptotic freedom reduce this numbe to just three and only three.
- Why is the electric charge quantized? As in the SM because classical and quantum constraint but unlike the SM it does not possible dequantized depending on the nature of the neutrinos, Dirac or Majorana.
- Why x= $sin^2\theta_W < 0.25$. Because the relation between the U(1) and SU(3) coupling constants

$\frac{g_X}{g} = \frac{1}{\sqrt{1-4x}}$, and there is a Landau-like pole when x=0.25

- The model has and almost authomatic Peccei-Quinn symmetry

TOO MANY SCALAR? INTERESTING EXTENSIONS OF THE SM ARE THOSE WITH MANY SCALARS, DOUBLETS, ONE TRIPLET, AND MANY SINGLETS

MANY PARAMETERS (AS MOST OF THE MODELS BEYOND THE SM): MORE FIELDS, MORE MIXING PARAMETERS (QUATUM MECHANICS: SYSTEM WITH THE SAME QUANTUM NUMBERS MUST MIX)

WHAT IS THE STANDARD MODEL LIMIT?

STANDARD MODEL EXTENSIONS

- Add right-handed neutrinos in
- Milti-Higgs extensions: with the same gauge symmetry of the SM: Singlet, doublet, triplet scalars are added.
- Largest symmetries: extra U(1), supersimetry, left-right symmetry, GUT,...

THEN TRY TO SOLVE SOME OF THE QUESTIONS THAT THE SM LEAVES OPEN

DEGREES OF FREEDOM DO NOT PRESENT IN THE SM:

FERMIONS: ONLY 3X3 COLORED QUARKS J, j_1, j_2

BOSONS: i) ONE NEUTRAL AND TWO CHARGED VECTOR BOSONS Z', V^-, U^{--},

$$\begin{pmatrix} W^3 + W^8 + B & W^+ & V^- \\ W^- & -W^3 + W^8 + B & U^{--} \\ V^+ & U^{++} & -W^8 + B \end{pmatrix}$$

ii) SCALARS: 3 SM-LIKE DOUBLETS, 1 CHARGED DOUBLET, 1 TRIPLET, FOUR SINGLETS
ONE OF THE LATTER ONES IS SINGLY CHARGED, TWO DOUBLY CHARGED,
AND ONE IS NEUTRAL

$$SU(3)_C \otimes SU(3)_L \otimes U(1)_X \rightarrow SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

v_χ

STANDARD MODEL FERMIONS

(MASSLESS FIELDS)

$$\begin{pmatrix} \nu_l \\ l \end{pmatrix}_L, \; l^c{}_L$$

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

$$u_R \quad c_R \quad t_R$$

$$d_R \quad s_R \quad b_R$$

$$\gamma \quad Z^0 \quad W^\pm$$

MASSIVE FIELDS

Vector quarks $J_{R,L} \quad j_{1,2\,R,L}$

Bosons $Z', V^+, \; U^{++}, \; \chi^0$

WHY SO MANY PARAMETERS?

fields appearing in multiplets are symmetry eigenstates. When the Higgs fields acquire a non zero VEV, quark mass terms are generated

KNOWN QUARKS $$M^q = M^q(Yukawa, v_\eta, v_\rho)$$

These are not normal matrices

$$[M^q, M^{q+}] \neq 0$$

MASS EIGENSTATES ARE OBTAINED BY DIAGONALIZING THE UP AND DOWN QUARKS MATRICES BY FOUR UNITARY MATRICES

$$\widehat{M}^q = V_L^{q+} M^q M_R^q \, , q = u, d$$

$$V_{CKM} = V_L^u \, V_L^{d+}$$

The unitary matrices survive in combinations different from the CKM matrix, in other interactions with extra vectors or scalar bosons.

IN THE SM ONLY THE COMBINATION

$$V_{CKM} = V_L^u \, V_L^{d+}$$

SURVIVES IN THE CHARGED CURRENT $W^{\pm}$ COUPLE TO THE UP AND DOWN MASS EIGENSTATES (THERE IS NO FCNC IN THE SM, GIM-MECHANISM)

It means that it is necessary to measure these matrices independently of the CKM!

PREDICTIONS OF 3-3-1 MODELS

● Leptophobic neutral vector boson Z'
● singly and doubly charged vector bosons $V^{\pm}, U^{\pm\pm}$
● quarks with electric charge 5/3 and -4/3 (in units of |e|)
● neutral, singly and doubly charged scalars in singlet, doublet and triplets
(all of them have been proposed in extensions of the SM)

[pdf, other]

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[arXiv:1603.05952 [hep-ph]].

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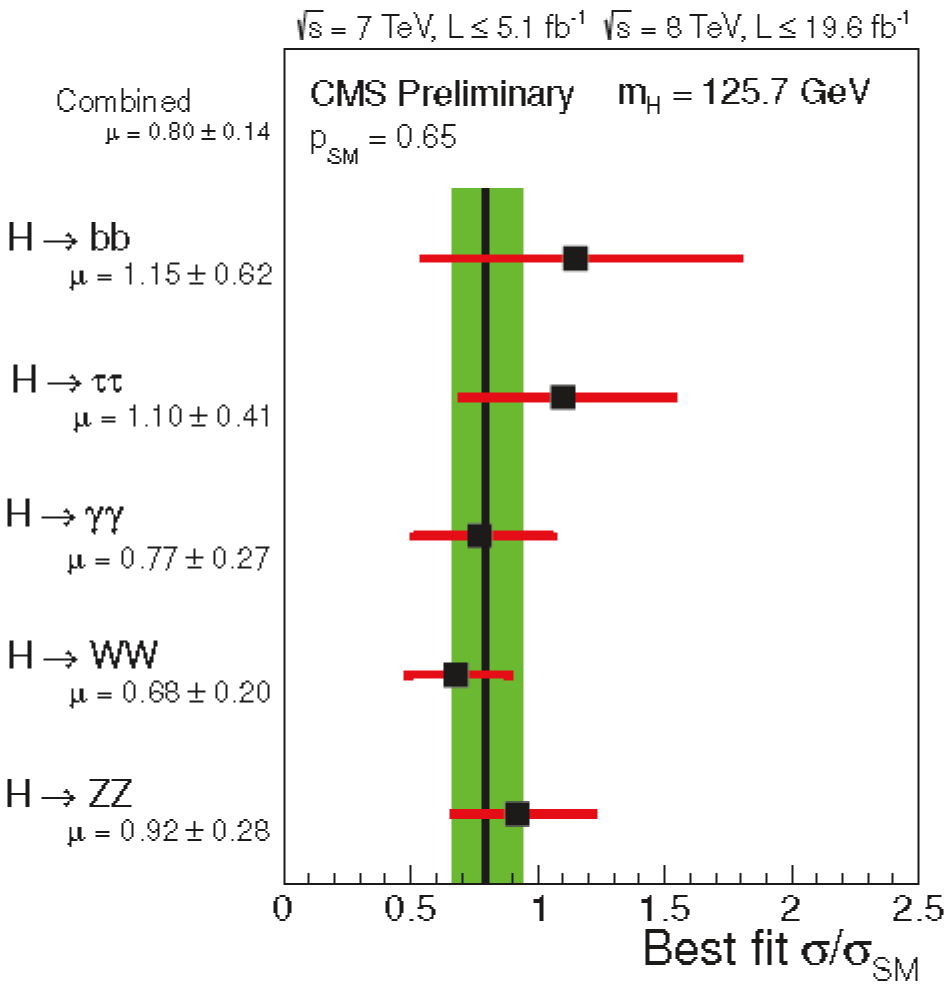

FERMIONS

$$\underset{\downarrow}{3}\quad \begin{pmatrix} \nu_l \\ l \\ l^c \end{pmatrix}_L \qquad \underset{\downarrow}{3^*}\quad \begin{pmatrix} d \\ -u \\ j_1 \end{pmatrix}_L \quad \underset{\downarrow}{3^*}\quad \begin{pmatrix} s \\ -c \\ j_2 \end{pmatrix}_L \quad \underset{\downarrow}{3}\quad \begin{pmatrix} t \\ b \\ J \end{pmatrix}_L$$

1 (singlets)

$$\underbrace{U_R, \quad D_R, \quad j_{1R}, j_{2R}, J_R}$$

All are still symmetry eigenstates. Notice that all known leptonic degrees of freedom are already included. Right-handed (sterile) neutrinos can be added as well.

This is the reason why the model is called MINIMAL 3-3-1 MODEL.

The price to be paid is the introduction of quarks with electric charge -4/3 (j's) and 5/3 (J)

Choose the leptons first X=0:

LEPTONS L=Diag($\nu_l \; l \; l^c$ $)_L$ l= e,μ,τ Three triplets x 3 → 9 degrees of fredom

ν_R are optional

Three quark triplets: 3x3x3=27 degrees of freedom (including color).
Let us arrange them as follows: 18 in anti-triplets 3^* and 9 in triplets 3

This makes the model free of SU(3) anomalies: there are 18 in antitriplets (3^*) and 18 In triplets 3 $A(3) = -A(3^*)$

Since (in this case the sum is over the quarks only)

$$Tr\, X = Tr\, X^3 = 0$$

the anomalies involving $U_1(X)$ cancel out

THE MODEL IS FREE OF ANOMALIES ONLY WHEN THE THREE GENERATIONS ARE TAKEN INTO ACCOUNT (ASYMPTOTIC FREEDOM IMPLIES 3 AND ONLY 3 GENERATIONS). THE SM IS FREE OF ANOMALY GENERATION PER GENERATION.