`Thank for the invitation`

ADDITIONAL BARYONS AND MESONS

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Introduction

In this talk we shall discuss what seems now to be a likely first BSM particle now being searched for actively at the LHC.

The bilepton model (a better name than 331-model) was invented as an example of a class of 3-family models which turned out to have only one distinct member. The probability LHC can find the bilepton signal in 2021 seems good.

We shall not have time to explain how this model was invented historically (see the references *ut supra*). We say only that to make an BSM model one generally aims for
(i) motivation usually by addressing a question unanswered within the Standard Model.
(ii) testability by explicit predictions.
Both are satisfied in the bilepton model.

Bilepton Model

The gauge group is:

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

The simplest choice for the electric charge is

$$Q = \frac{1}{2}\lambda_L^3 + \left(\frac{\sqrt{3}}{2}\right)\lambda_L^8 + X\left(\frac{\sqrt{3}}{\sqrt{2}}\right)\lambda^9$$

where

$$Tr(\lambda_L^a \lambda_L^b) = 2\delta^{ab}$$

and

$$\lambda^9 = \left(\frac{\sqrt{2}}{\sqrt{3}}\right) \quad \mathrm{diag}(1, 1, 1)$$

Thus a triplet has charges $(X+1, X, X-1)$.

Leptons are treated democratically in each of the three families. They are colour singlets in antitriplets of $SU(3)_L$:

$$(e^+, \nu_e, e^-)_L$$
$$(\mu^+, \nu_\mu, \mu^-)_L$$
$$(\tau^+, \nu_\tau, \tau^-)_L$$

All have $X = 0$.

Quarks in the first family are colour triplets and left-handed triplets plus three singlets

$$(u^\alpha, d^\alpha, D^\alpha)_L \quad (\bar{u}_\alpha)_L, (\bar{d}_\alpha)_L, (\bar{D}_\alpha)_L$$

Similarly for the second family

$$(c^\alpha, s^\alpha, S^\alpha)_L \quad (\bar{c}_\alpha)_L, (\bar{s}_\alpha)_L, (\bar{S}_\alpha)_L$$

The X values are for the triplets are $X = -1/3$ and for the singlets $X = -2/3, +1/3, +4/3$ respectively. The electric charge of the new quarks D, S is $-4/3$.

The quarks of the third family are treated differently. The color triplet quarks are in a left-handed antitriplet and three singlets under $SU(3)_L$

$$(b^\alpha, t^\alpha, T^\alpha)_L \quad (\bar{b}_\alpha)_L, (\bar{t}_\alpha)_L, (\bar{T}_\alpha)_L$$

The antitriplet has $X = +2/3$ and the singlets carry $X = +1/3, -2/3, -5/3$ respectively. The new quark T has $Q = 5/3$.

A central question in high-energy physics is what will be the first new particle to be discovered beyond the standard model. In this talk, we discuss how it could impact on particle phenomenology beyond the TeV energy scale.

The minimal 331-model with no additional leptons, as proposed in (Frampton, 1992) involves, *inter alia*, doubly-charged gauge bosons $Y^{\pm\pm}$ with lepton number $|L| = 2$ which decay into same-sign leptons and are being sought at the LHC. Some of the relevant LHC phenomenology is discussed in the references listed *ut supra*. A refined mass estimate for the bilepton is is $M(Y^{\pm\pm}) = (1.29 \pm 0.06)$ TeV where *faute de mieux* it was assumed that the symmetry breaking of $SU(3)_L$ is closely similar to that of $SU(2)_L$. It will be pleasing if the physical mass is consistent with this.

New Quarks

Because the quarks are in triplets and anti-triplets of $SU(3)_L$, rather than only in doublets of $SU(2)_L$ as in the standard model, there is necessarily an additional quark in each family. In the first and second families they are the $\mathcal{D}$ and $\mathcal{S}$ respectively, both with charge $Q = -4/3$ and lepton number $L = +2$. In the third family is the $\mathcal{T}$ with charge $Q = +5/3$ and lepton number $L = -2$. All the three TeV scale quarks are colour triplets with spin-$\frac{1}{2}$ and baryon number $B = \frac{1}{3}$. Their masses are yet to be measured but may be expected to be below the ceiling of $4.1TeV$ which is the upper limit for symmetry breaking of $SU(3)_L$ and probably above $1TeV$. By analogy with the known quarks, one might expect $M(\mathcal{T}) > M(\mathcal{S}) > M(\mathcal{D})$, although without experimental data this is conjecture.

The heavy quarks and antiquarks will be bound to light quarks and antiquarks, and to each other, to form an interesting spectroscopy of mesons and baryons. Let us first display, in Tables 1, 2 the TeV mesons, then in Tables 3,4,5 the TeV baryons. The charge conjugate states are equally expected, and will reverse the signs of Q and L.

Additional Baryons and Mesons.

Table 1: TeV mesons $\mathcal{Q}\bar{q}$

$\mathcal{Q}$	$\bar{q}$	Q	L
$\mathcal{D}/\mathcal{S}$	$\bar{u}$ etc.	-2	+2
$\mathcal{D}/\mathcal{S}$	$\bar{d}$ etc.	-1	+2
$\mathcal{T}$	$\bar{u}$ etc.	+1	-2
$\mathcal{T}$	$\bar{d}$ etc.	+2	-2

Table 2: TeV mesons $\mathcal{Q}\bar{\mathcal{Q}}$

$\mathcal{Q}$	$\bar{\mathcal{Q}}$	Q	L
$\mathcal{D}/\mathcal{S}$	$\bar{\mathcal{D}}/\bar{\mathcal{S}}$	0	0
$\mathcal{D}/\mathcal{S}$	$\bar{\mathcal{T}}$	-3	+4
$\mathcal{T}$	$\bar{T}$	0	0

Table 3: TeV baryons $\mathcal{Q}qq$

$\mathcal{Q}$	qq	Q	L
$\mathcal{D}/\mathcal{S}$	dd etc.	-2	+2
$\mathcal{D}/\mathcal{S}$	ud etc.	-1	+2
$\mathcal{D}/\mathcal{S}$	uu etc.	0	+2
$\mathcal{T}$	dd etc.	+1	-2
$\mathcal{T}$	ud etc.	+2	-2
$\mathcal{T}$	uu etc,	+3	-2

Table 4: TeV baryons $\mathcal{Q}\mathcal{Q}q$

$\mathcal{Q}\mathcal{Q}$	q	Q	L
$(\mathcal{D}/\mathcal{S})(\mathcal{D}/\mathcal{S})$	d etc.	-3	+4
$(\mathcal{D}/\mathcal{S})(\mathcal{D}/\mathcal{S})$	u etc.	-2	+4
$(\mathcal{D}/\mathcal{S})\mathcal{T}$	d etc.	0	0
$(\mathcal{D}/\mathcal{S})\mathcal{T}$	u etc.	+1	0
$\mathcal{T}\mathcal{T}$	d etc.	+3	-4
$\mathcal{T}\mathcal{T}$	u etc.	+4	-4

Table 5: TeV baryons $\mathcal{Q}\mathcal{Q}\mathcal{Q}$

$\mathcal{Q}\mathcal{Q}\mathcal{Q}$	Q	L
$(\mathcal{D}/\mathcal{S})(\mathcal{D}/\mathcal{S})(\mathcal{D}/\mathcal{S})$	-4	+6
$(\mathcal{D}/\mathcal{S})(\mathcal{D}/\mathcal{S})\mathcal{T}$	-1	+2
$(\mathcal{D}/\mathcal{S})\mathcal{T}\mathcal{T}$	+2	-2
$\mathcal{T}\mathcal{T}\mathcal{T}$	+5	-6

Although the $\mathcal{Q}$ masses are unknown, it may be reasonable first to make a preliminary discussion of these states by assuming that

$$M(\mathcal{T}) > M(\mathcal{S}) + 2M_t > M(\mathcal{D}) + 4M_t \quad (1)$$

where M_t is the top quark mass so that the lightest of the TeV baryons and mesons are those containing just one $\mathcal{D}$ quark or one $\bar{\mathcal{D}}$ antiquark. The next lightest are the TeV baryons and mesons containing just one $\mathcal{S}$ quark or one $\bar{\mathcal{S}}$ antiquark.

We begin by discussing the decay modes of the $\mathcal{D}\bar{q}$ mesons in Table 1, focusing on final states from the first family. The decays of $\mathcal{D}$ include, taking care of L conservation,

$$\begin{aligned}
\mathcal{D} &\rightarrow d + Y^- \\
&\rightarrow d + (e^- + \nu_e) \\
&\rightarrow d + (\mu^- + \nu_\mu) \\
&\rightarrow d + (\tau^- + \nu_\tau)
\end{aligned} \tag{2}$$

which implies that decays of the $(\mathcal{D}\bar{u})$ meson include

$$\begin{aligned}
(\mathcal{D}\bar{u}) &\rightarrow \pi^- + (e^- + \nu_e) \\
&\rightarrow \pi^- + (\mu^- + \nu_\mu) \\
&\rightarrow \pi^- + (\tau^- + \nu_\tau)
\end{aligned} \tag{3}$$

and variants thereof where π^- is replaced by any other non-strange negatively charged meson. The d in Eq.(2) can be replaced by s or b which subsequently decay.

An alternative to Eq.(2) is

$$\begin{aligned} \mathcal{D} &\rightarrow u + Y^{--} \\ &\rightarrow u + (e^- + e^-) \\ &\rightarrow u + (\mu^- + \mu^-) \\ &\rightarrow u + (\tau^- + \tau^-) \end{aligned} \tag{4}$$

which implies additional decay modes of the $(\mathcal{D}\bar{u})$ meson which include

$$\begin{aligned} (\mathcal{D}\bar{u}) &\rightarrow \pi^0 + (e^- + e^-) \\ &\rightarrow \pi^0 + (\mu^- + \mu^-) \\ &\rightarrow \pi^0 + (\tau^- + \tau^-) \end{aligned} \tag{5}$$

and variants obtained by flavour replacements. Eqs.(3) and (5), and their generalisations to other flavours, suffice to illustrate the richness of $(\mathcal{D}\bar{u})$ decays.

Turning to the meson $\mathcal{D}\bar{d}$, we can use Eq.(2) to identify amongst its possible decays

$$\begin{aligned}(\mathcal{D}\bar{d}) &\rightarrow \pi^0 + (e^- + \nu_e)\\ &\rightarrow \pi^0 + (\mu^- + \nu_\mu)\\ &\rightarrow \pi^0 + (\tau^- + \nu_\tau)\end{aligned} \tag{6}$$

and variants thereof where π^0 is replaced by any other non-strange neutral meson. When u in Eq.(2) is replaced by c or t which subsequently decay, we arrive at many other decay channels additional to Eq.(6).

Employing instead the $\mathcal{D}$ decays in Eq.(4) implies additional decay modes of $(\mathcal{D}\bar{d})$ meson that include

$$\begin{aligned}(\mathcal{D}\bar{d}) &\rightarrow \pi^+ + (e^- + e^-)\\ &\rightarrow \pi^+ + (\mu^- + \mu^-)\\ &\rightarrow \pi^+ + (\tau^- + \tau^-)\end{aligned} \tag{7}$$

and variants obtained by flavour replacement. Eqs.(6) and (7), merely illustrate a few of the simplest $(\mathcal{D}\bar{d})$ decays. There are many more.

Next we consider the lightest TeV baryons in Table 3 with $\mathcal{Q} = \mathcal{D}$. Using the $\mathcal{D}$ decays from Eq.(2) we find for $(\mathcal{D}uu)$ decay

$$(\mathcal{D}uu) \rightarrow p + (l_i^- + \nu_i). \tag{8}$$

together with flavour rearrangements. Here, as in subsequent equations, $i = e, \mu, \tau$.

Alternatively, the $\mathcal{D}$ decays from Eq.(4) lead to

$$\begin{aligned}(\mathcal{D}uu) &\rightarrow N^{*++} + Y^{--}. \\ &\rightarrow p + \pi^+ + (l_i^- + l_i^-)..\end{aligned} \tag{9}$$

Looking at the TeV baryon $(\mathcal{D}ud)$ the respective sets of decays corresponding to Eq.(2) are

$$(\mathcal{D}ud) \rightarrow n + (l_i^- + \nu_i) \tag{10}$$

where only the simplest light baryon is exhibited.

Corresponding to $\mathcal{D}$ decays in Eq.(4) there are also

$$(\mathcal{D}ud) \rightarrow p + (l_i^- + l_i^-) \tag{11}$$

in the simplest cases.

Finally, of the $(\mathcal{D}qq)$ TeV baryons, we write out the decays for $(\mathcal{D}dd)$, first for the $\mathcal{D}$ decays in Eq.(2)

$$\begin{aligned}(\mathcal{D}dd) &\rightarrow N^{*-} + Y^- \\ &\rightarrow n + \pi^- + (l_i^- + \nu_i).\end{aligned} \tag{12}$$

within flavour variations.

With the $\mathcal{D}$ decay modes in Eq.(4) there are also decays

$$(\mathcal{D}dd) \rightarrow n + (l_i^- + l_i^-) \tag{13}$$

again with more possibilities by choosing alternative flavours.

We now replace the TeV quark $\mathcal{D}$ by the next heavier TeV quark $\mathcal{S}$ and repeat our study of decays whereupon we shall encounter the first example of decay not only to the known quarks but also to a TeV quark.

The TeV quark $\mathcal{S}$ has possible decay channels

$$\begin{aligned}
\mathcal{S} &\rightarrow d + Y^- \\
&\rightarrow d + (e^- + \nu_e) \\
&\rightarrow d + (\mu^- + \nu_\mu) \\
&\rightarrow d + (\tau^- + \nu_\tau) \\
&\rightarrow \mathcal{D} + Z' \\
&\rightarrow d + (e^- + \nu_e) + (e^+ + e^-) \\
&\rightarrow d + (e^- + \nu_e) + (\mu^+ + \mu^-) \\
&\rightarrow d + (e^- + \nu_e) + (\tau^+ + \tau^-) \\
&\rightarrow d + (\mu^- + \nu_\mu) + (e^+ + e^-) \\
&\rightarrow d + (\mu^- + \nu_\mu) + (\mu^+ + \mu^-) \\
&\rightarrow d + (\mu^- + \nu_\mu) + (\tau^+ + \tau^-) \\
&\rightarrow d + (\tau^- + \nu_\tau) + (e^+ + e^-) \\
&\rightarrow d + (\tau^- + \nu_\tau) + (\mu^+ + \mu^-) \\
&\rightarrow d + (\tau^- + \nu_\tau) + (\tau^+ + \tau^-)
\end{aligned} \tag{14}$$

where we note the opening up of channels due to $\mathcal{S} \rightarrow \mathcal{D}$ decay.

With Eq.(14) in mind, the decays of the TeV meson $(\mathcal{S}\bar{u})$ include

$$\begin{aligned}(\mathcal{S}\bar{u}) &\rightarrow \pi^- + (l_i^- + \nu_i) \\ &\rightarrow \pi^- + (l_i^- + \nu_i) + (l_j^+ + l_j^-)\end{aligned} \tag{15}$$

where the second line involves a $\mathcal{D}$ intermediary.

An alternative to Eq.(14) is

$$\begin{aligned}\mathcal{S} &\rightarrow u + Y^{--} \\ &\rightarrow u + (e^- + e^-) \\ &\rightarrow u + (\mu^- + \mu^-) \\ &\rightarrow u + (\tau^- + \tau^-)\end{aligned} \tag{16}$$

which implies additional decay modes of $(\mathcal{S}\bar{u})$

$$(\mathcal{S}\bar{u}) \rightarrow \pi^0 + (l_i^- + l_i^-) \tag{17}$$

and variants which replace π^0 by another neutral non-strange meson. Eqs.(15) and (17), illustrate sufficiently $(\mathcal{S}\bar{u})$ decays.

Turning to the meson $(\mathcal{S}\bar{d})$, we can use Eq.(14) to identify its possible decays

$$(\mathcal{S}\bar{d}) \rightarrow \pi^0 + (l_i^- + \nu_i) \tag{18}$$

When u in Eq.(14) is replaced by c or t which subsequently decay, we arrive at many other decay channels additional to Eq.(18).

Employing instead the $\mathcal{S}$ decays in Eq.(16) implies additional decay modes of $(\mathcal{S}\bar{d})$ that include

$$(\mathcal{S}\bar{d}) \rightarrow \pi^+ + (l_i^- + l_i^-) \tag{19}$$

and variants obtained by flavour replacement. Eqs.(18) and (19), illustrate only a few of the simplest $(\mathcal{S}\bar{d})$ decays. There are many more.

Next we consider the lightest TeV baryons in Table 3 with one $\mathcal{Q} = \mathcal{S}$. Using the $\mathcal{S}$ decays from Eq.(14) we find for $(\mathcal{S}uu)$ decay

$$(\mathcal{S}uu) \to p + (l_i^- + \nu_i). \tag{20}$$

together with flavour rearrangements.

Alternatively, the $\mathcal{S}$ decays from Eq.(16) lead to

$$\begin{aligned} (\mathcal{S}uu) &\to N^{*++} + (l_i^- + l_i^-).. \\ &\to p + \pi^+ + (l_i^- + l_i^-). \end{aligned} \tag{21}$$

Looking at the TeV baryon $(\mathcal{S}ud)$ the respective sets of decays corresponding to Eq.(14) are

$$(\mathcal{S}ud) \rightarrow n + (l_i^- + \nu_i) \tag{22}$$

where only the simplest version is exhibited.

Corresponding to the $\mathcal{S}$ decays in Eq.(16) there are the decays

$$(\mathcal{S}ud) \rightarrow p + (l_i^- + l_i^-) \tag{23}$$

For baryon $(\mathcal{S}dd)$, firstly from the $\mathcal{S}$ decays in Eq.(14) we have

$$\begin{aligned}(\mathcal{S}dd) &\rightarrow N^{*-} + Y^- \\ &\rightarrow n + \pi^- + (l_i^- + \nu_i).\end{aligned} \tag{24}$$

within flavour variations.

Secondly, from the Eq.(16) decays of $\mathcal{S}$ there are baryon decays of the type

$$(\mathcal{S}dd) \rightarrow n + (l_i^- + l_i^-) \tag{25}$$

with more possibilities by choosing alternative flavours.

Discussion

We could continue further to study decays of all the baryons and mesons in our Tables. However, it seems premature to do so until we know from experimental data the masses and mixings of $\mathcal{D}, \mathcal{S}, \mathcal{T}$. We remark only that the type of lepton cascade which we have deliberately exhibited explicitly in Eq.(14) becomes a more prevalent possibility as the lepton number of the decaying hadron increases.

We may expect, by analogy with the top quark, that the mass of the $\mathcal{T}$ quark, although probably below 4.1 TeV for the symmetry-breaking reason discussed *ut supra* might be not much below. For example it might exceed 3 TeV whereupon the mass of a $(\mathcal{TTT})$ baryon could exceed 9 TeV. Since this baryon has high lepton number, it is pair produced and such pair production is beyond the reach of the 14 TeV LHC. Its study requires a 100 TeV collider of the type under discussion at CERN and in China. As a foretaste of the physics, one notable decay of the $(\mathcal{TTT})$ baryon is into

$$p + 4(e^{+}) + 2(\bar{\nu}_e).$$

At the time of this talk, the particles exhibited in our Tables are conjectural. If and when the bilepton is established as the first new elementary particle discovered since 2012, the existence of all the additional baryons and mesons will become a sharp prediction.

`Thank you for your attention`