`Thank for the invitation`

DOUBLY-CHARGED BILEPTONS
AT THE
LARGE HADRON COLLIDER

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C. Coriano and P.H. Frampton,
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`arXiv:1812.02723[hep-ph]`.

Introduction

Because the most popular theoretical model aiming beyond the standard model - supersymmetry - have received no encouragement from LHC data, in this talk we shall discuss what is now a more likely type of BSM particle.

The bilepton model was invented 27 years ago as merely one exemplar of what was at the time expected to be a new class of models.

In 2019, either the LHC fails to find any BSM particle (hopefully 90% unlikely) or the bilepton model is probably correct.

`Very optimistically, it could be three or four chances out of five that bileptons exist.`

We shall explain how this model was invented historically because there is no Royal Road to model building. One generally aims for
(i) motivation usually by addressing a question unanswered within the Standard Model.
(ii) testability by unambiguous experimental predictions.

We shall first step back and discuss generalities about Quantum Field Theory.

Quantum Field Theory (QFT)

QFT is the marriage of two successful theories:

(i) Special Relativity
(ii) Quantum Mechanics

both of which made many predictions which agree with experiment.

QFT is a merely a mathematical framework which, without further input, cannot make any prediction to be compared with experiment – when parity is conserved.

As we shall discuss, when parity is violated as in weak interactions, QFT does acquire non-trivial predictive power.

Gauge Field Theories (GFT)

Quantum Electrodynamics (QED) most accurate comparison with experiment.

Anomalous electron magnetic moment $(g-2)_e$ agrees to $0.65ppb$. The one-loop correction was calculated in 1948 independently by Nambu (unpublished) and by Schwinger (epitaph).

Two good papers by Yang went beyond QED:

C.N. Yang and R.L. Mills,
Conservation of Isotopic Spin and Isotopic Gauge Invariance. Phys. Rev. **96,** 191 (1954).
The more important of the two papers.
Led to twenty Nobel prizes.

T.D. Lee and C.N. Yang,
Question of Parity Conservation in Weak Interactions. Phys. Rev. **104,** 254 (1956).
Nobel prize 1957.
Clearly explained in Physics Today.

The generalization of GFT to non-abelian groups allows the successful accommodation of strong (QCD) and weak interactions. QED and QCD conserve parity. Quarks and leptons can be successfully described in QCD and QED by Dirac fermions.

The fact that weak interactions violate parity means that the couplings of the weak gauge bosons Z^0 and $W^{\pm}$ in an electroweak theory must be made to quarks and leptons described by chiral fermions. In this talk, ν's are treated as if massless, to avoid distracting digressions.

Chiral fermions lead to a consistency requirement: cancellation of triangle anomalies, a necessary condition for unitarity.

Triangle anomaly cancellation is the only physics prediction arising from the mathematics of QFT.

Can it predict three quark-lepton families?

Consider the first family of the SM :

$$(u^\alpha \; d^\alpha)_L \quad \bar{u}_{L\alpha} \quad \bar{d}_{L\alpha} \quad (\nu_e \; e)_L \quad \bar{e}_L$$

15 chiral fermions. Define $Q = T_3 + \frac{1}{2}Y$ so the five $SU(3)_{QCD} \times (SU(2) \times U(1))_{EW}$ irreducible representations have Y values

$$\left(+\frac{1}{3}\right) \quad \left(-\frac{4}{3}\right) \quad \left(+\frac{2}{3}\right) \quad (-1) \quad (+2)$$

The Y^3 anomaly is proportional to

$$6\left(\frac{+1}{3}\right)^3 + 3\left(\frac{-4}{3}\right)^3 + 3\left(\frac{+2}{3}\right)^3 + 2(-1)^3 + (+2)^3$$

$$= \frac{1}{27}(+6 - 192 + 24) - 2 + 8 = \frac{-162}{27} + 6 = 0.$$

A diophantine equation for the Y values.

The arrangement of the 3-2-1 quarks and leptons in one family is such that the triangle anomalies cancel between quarks and leptons neither of which separately cancel.

What could be more natural than that the occurrence of the <u>three</u> families is because of inter-family triangle anomaly cancellation?

Simple to state, challenging to solve.

TRIANGLE ANOMALIES

J. Steinberger, *On the Use of Subtraction Fields and the Lifetimes of Some Types of of Meson Decay*. Phys. Rev. **76,** 1180 (1949).
`Author changed to experiment`

S.L. Adler, *Axial Vector Vertex in Spinor Electrodynamics.*
Phys. Rev. **177,** 2426 (1969).
`Definitive paper`

J.S. Bell and R. Jackiw, *A PCAC Puzzle:* $\pi^0 \to \gamma\gamma$ *in the Sigma Model.*
Nuovo Cimento **A60,** 47 (1969).
`Tried to remove anomaly.`

C. Bouchiat, J. Iliopoulos and P. Meyer,
An Anomaly-Free Version of Weinberg's Model.
Phys. Lett. **38B,** 519 (1972).
`Back-up to GIM prediction of charm quark`

Chalkboard discussion of triangle anomaly.

Before coming to the 3-3-1 or bilepton model, we shall discuss the minimal SU(5) GUT then the SU(15) GUT within which bileptons first appeared.

SU(5) Grand Unification (GUT)

15 chiral states are placed in the anomaly-free SU(5) reducible representation:

$$\mathbf{10}_L + \bar{\mathbf{5}}_L$$

Anomalies:

SU(3) 1 -1
SU(4) 1 0 -1
SU(5) 1 1 -1 -1
SU(6) 1 2 0 -2 -1
SU(7) 1 3 2 –2 -3 -1
SU(8) 1 4 5 0 -5 -4 -1
SU(9) 1 5 9 5 -5 -9 -5 -1

Displaced Pascal triangle.

Note that the SU(5) anomaly cancels $1 - 1 = 0$ within each family.

Under the Standard Model gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \subset SU(5)$ representations 10 and $\bar{5}$ decompose as:

$$10 = (3, 2, 1/6)_L + (\bar{3}, 1, -2/3)_L + (1, 1, 1)_L$$

and

$$\bar{5} = (\bar{3}, 1, 1/3)_L + (1, 2, -1/2)_L$$

accommodating the SM quantum numbers.

SU(5) predicts proton decay $p \rightarrow e^+\pi^0$ by tree-level gauge boson exchange with lifetime

$$\tau_p < 10^{31} y$$

However, in 1984 the Irvine-Michigan-Brookhaven Collaboration announced that $\tau_p > 10^{32} y$ and SuperKamiokande has shown that

$$\tau_p > 2 \times 10^{34} y$$

while HyperKamiokande will gain one more order of magnitude.
This kills the minimal SU(5) GUT theory.

One *ad hoc* attempt to accommodate the proton lifetime within a generalization of minimal SU(5) appeared in
Staying Alive with SU(5)
Phys. Lett. **B131,** 340 (1985),
with Glashow.

Also, SU(N) GUTs were invented with generalised fundamental representations *e.g.*

$$SU(9): \qquad \mathbf{84} + 9(\bar{\mathbf{9}})$$

which is free of triangle anomalies (see the displaced Pascal triangle) and is the simplest such theory with 3 families.

Shortly after the demise of minimal GUT came the first superstring revolution, and a sea change in popularity toward mathematical supertheory.

Brief digression on super-theories :

supersymmetry, supergravity, superstrings.

We contributed to string theory.

1974 First book on string theory.

`Sales in 1979 and 1986`

1983 Hexagon anomaly +T.Kephart.

`First appearance of O(32).`

1988 P-adic string +Y.Okada

`First use of prime numbers`

HEXAGON ANOMALY IN D=10

P.H. Frampton and T.W. Kephart,
Explicit Evaluation of Anomalies
in Higher Dimensions.
Phys. Rev. Lett. **50,** 1343 (1983).

P.H. Frampton and T.W. Kephart,
The Analysis of Anomalies in Higher Space-Time Dimensions.
Phys. Rev. **D28,** 1010 (1983)
`O(32) is in the Appendix`

M.B. Green and J.H. Schwarz,
Anomaly Cancellation in Supersymmetric D=10
Gauge Theory and Superstring Theory.
Phys. Lett. **149B,** 117 (1984).

Chalkboard discussion of hexagon anomaly.

SU(15) Grand Unification

`with Bum-Hoon Lee`

Motivated by proton decay we avoid tree-level gauge-mediated diagram by using **15** of SU(15) for each family.

$$\mathbf{15} = (u_R, u_G, u_B; d_R, d_G, d_B; \bar{u}_R, \bar{u}_G, \bar{u}_B; \bar{d}_R, \bar{d}_G, \bar{d}_B; e^+, \nu_e, e^-)_L$$

The gauge bosons of SU(15) each couple to a specific pair of fermions. The GUT scale can be reduced with

$$SU(15) \rightarrow SU(12)_q \times SU(3)_l$$

as low as 10^7 GeV, with subsequent breaking to $SU(6)_L \times SU(6)_R \times U(1)_h \times SU(3)_l$ and thence to the Standard Model.

This is accomplished by scalars in **224**'s and **15**'s.

However, such a model has triangle anomalies which must be canceled by mirror fermions:

$$\mathbf{15} + \bar{\mathbf{15}}$$

which is aesthetically unattractive and because of this we would not consider SU(15) grand unification as a realistic model.

Nevertheless, it was by assiduous study of the SU(15) GUT model that two years later we arrived at the far more interesting Bilepton Model

The fundamental triplet of the leptonic $SU(3)_l$ is worth studying:

$$(e^+, \nu_e, e^-)_L$$

The gauge bosons of $SU(3)_l$ include the four BILEPTONS

$$(Y^{--}, Y^-) \qquad\qquad L = +2$$

and

$$(Y^{++}, Y^+) \qquad\qquad L = -2$$

This gives rise to a very interesting question: does there exist a chiral model containing such bileptons and with non-trivial cancelation of triangle anomalies?

The answer is yes and was provided (after $\sim$ 100 tries) by the Bilepton Model.

Bilepton (331) Model

The gauge group is:

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

`Hence the name`

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 <u>antitriplet</u> 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 $Q = 5/3$.

Before discussing the symmetry breaking to $SU(2)_L \times U(1)_Y$ and the resulting mass spectrum, we shall explain the nontrivial anomaly cancellation of this model.

There are six triangle anomalies which are potentially troublesome; in a self-explanatory notation these are diophantine equations

$(3_C)^3, (3_C)^2X, (3_L)^3, (3L)^2X, X^3, X$.

The QCD anomaly $(3_C)^3$ is absent because QCD is, as usual, vectorlike. $(3_C)^2X$ vanishes because the quarks are in nine color triplets with net $X = 0$ and nine antitriplets also with net $X = 0$. The pure $(3_L)^3$ anomaly vanishes because there is an equal number of 3_L and 3^*_L. $(3_L)^2X$ cancels because the leptons have X =0 and the quarks are in six triplets 3_L with $X = -\frac{1}{3}$ and three antitriplets 3^*_L with $X = +\frac{2}{3}$.

The X^3 cancellation can be checked by a little algebra: the three quark families contribute, respectively, $+6+6-12=0$.

It is especially interesting that this anomaly cancellation takes place between families. Each individual family possesses nonvanishing $(3_L)^3$, $(3L)^2X$, X^3 anomalies.

Only with the number of families a multiple of three does the overall anomaly vanish and asymptotic freedom of QCD dictates that the number be exactly three.

The symmetry breaking to the standard model is achieved by a Vacuum Expectation Value (VEV) of an $X = +1$ triplet $< \Phi^a >= U\delta^{a3}$. This gives mass $\Lambda_{D,S,T}U$ to the new quarks D, S, T where Λ_i are the Yukawa couplings. It also provides mass to five gauge bosons: the bileptons $(Y^{\pm\pm}, Y^{\pm})$ and $Z^{'}$.

Electroweak breaking is achieved by VEVs of two triplets $< \phi^a >= v\delta^{a2}$ (with $X = 0$) and $< \phi^{'a} >= v^{'}\delta^{a1}$ (with $X = -1$) and a doublet VEV in a sextet with $X = 0$
$< H^{\alpha\beta} >= y\sqrt{10}(\delta^{\alpha 1}\delta^{\beta 3} + \delta^{\alpha 3}\delta^{\beta 1})$

We note that because of global L symmetry, the W^+ and Y^+ do not mix. For the same reason, the new quarks with exotic charges (D, S, T) have lepton numbers $(+2, +2, -2)$ respectively.

Let the scale of breaking 331 → 321 be μ. To avoid imaginary coupling constants with $g_i^2 < 0$ which violate unitarity it is necessary to impose an upper limit on μ such that

$$\sin^2\theta(\mu) \leq \frac{1}{4}$$

while at the Z pole the value is

$$\sin^2\theta(M_Z) \simeq 0.231$$

which increases using the renormalisation group to $\frac{1}{4}$ at $\mu \simeq 4TeV$. Adopting this leads to

$$M_{Y^{\pm\pm}} \leq 2TeV$$

by analogy with the electroweak theory where $M(W^{\pm}) = 80GeV < 248GeV/2$.

This upper limit on mass is good news for the forthcoming LHC discovery of bileptons.

Lower Limit on Bilepton Mass

Perhaps surprisingly the lower limit comes not from colliders but from two table-top experiments.

Concidentally both experiments have been done at PSI (= Paul Scherrer Institute). A second coincidence is they both give closely the same result for the bilepton lower mass bound.

Firstly there is $\mu^+e^- \rightarrow \mu^-e^+$ which can be mediated by doubly-charged bilepton exchange. Called muonium-antimuonium conversion it provides $m_{Y^{\pm\pm}} > 800GeV$.

Secondly there is $\mu^- \rightarrow e^-\nu_e\bar{\nu}_\mu$ mediated by singly-charged bilepton exchange which by Fierz rearrangement is a $(V+A)$ contribution to $\mu^- \rightarrow e^-\bar{\mu}_e\nu_\mu$ whose Michel parameter ξ in $(V-\xi A)$ is $1 \geq \xi > 0.997$. This requires that $m_{Y^\pm} > 800GeV$.

Bilepton Phenomenology at the LHC

G. Corcella, C. Coriano, A. Costantini and P.H. Frampton, *Bilepton Signatures at the LHC*. Phys. Lett. **B773,** 544 (2017).

A study of bilepton pair production and two or more jets at the LHC with $\sqrt{s} = 13$ TeV using Feynman rules from the Bilepton Model.

About 3000 tree-level Feynman graphs
implemented by SARAH 4.9.3.
Amplitudes computed numerically
by MadGraph.
Simulation of parton showers and
hadronisation by HERWIG.

Notes:
1. $Z^{'}$ is leptophobic and so wide ($\Gamma \sim M$) that it is ill-defined for experimental verification.
2. Production and decay of new scalars were not discussed because they are less specific to the Bilepton Model.

Benchmark Point

SCALARS

$m_{h_1} = 125.1 GeV$ Higgs boson

$m_{h_2} = 3172 GeV$

$m_{h_3} = 3610 GeV$

$m_{h_1^\pm} = 1857 GeV$

$m_{h_2^\pm} = 3590 GeV$

$m_{h_1^{\pm\pm}} = 3734 GeV$

$m_{a_1} = 3595 GeV$

GAUGE BOSONS

$m_{Y^{\pm\pm}} = 873.3 GeV$

$m_{Y^\pm} = 875.7 GeV$

$m_{Z'} = 3229 GeV$

NEW QUARKS

$m_D = 1650 GeV$

$m_S = 1660 GeV$

$m_T = 1700 GeV$

Chalkboard discussion of bilepton signatures.

LHC Experimentalists

ATLAS

`Gabriel Facini`
Exotics convenor for ATLAS.
`Christina Sutton`. (Cambridge)
Searching for bileptons in ATLAS data.

CERN DG

`Fabiola Gianotti`
Email exchanges. Formerly with ATLAS,
cannot now show bias respecting CMS.

CMS

`Jim Virdee`
Discussed stiff muons with four tesla.
`Tomasso Dorigo, Ugo Gasperini,`
`and Mia Tosi` (Padova)
Discussing search for bileptons .

Resonance Bumps

Our method of estimating the numbers of events at ATLAS is to use old ATLAS data which were analysed to search for a SSM(=Sequential Standard Model) $Z^{'}$ which was not discovered. There is some similarity between production of Y and $Z^{'}$. The biggest difference is that Y must be pair produced so we approximate by using $\sigma_{SSM}^{Z^{'}}(M(Z^{'} = 2M(Y))$. We need to estimate the brancing ratio (BR) for $(Y \rightarrow e^{+}e^{+}, \mu^{+}\mu^{+}, \tau^{+}\tau^{+})$. Because there exist non-leptonic decays $B \rightarrow Q\bar{q}, q\bar{Q}$ where Q is an exotic quark, the BRs depend on the mass M(Q) of the exotic quarks.

Table 1: Branching ratio for bilepton Y^{++} decay into like-sign leptons, with BR($Y^{++} \to \tau^+\tau^+$) =BR($Y^{++} \to \mu^+\mu^+$)=BR($Y^{++} \to e^+e^+$). Assumes exotic quark mass $M(Q) =$ 800 GeV for all three families.

M(Y) GeV	BR=branching ratio into like-sign lepton pair (per flavour)
800	0.33
1100	0.31
1400	0.28
1700	0.25
2000	0.21

We re-calculate the numbers of S=signal events and B=background events, using the values of BR from Table 1. The results which are our most reliable predictions for the LHC are displayed in Table 2.

Table 2: Numbers of signal and background events at resonance in like-sign lepton pairs, calculated as explained in the text (C) for integrated luminosity 150/fm. This Table gives our most reliable predictions.

M(Y) GeV	$\sigma^{Z'}_{SSM}(M_{Z'} = 2M(Y))$ (fb)	$(BR)^2$	Signal events	Background events.
800	100	0.109	1635	< 0.01
1100	20	0.096	288	< 0.01
1400	6	0.078	70	< 0.01
1700	1	0.062	9	< 0.01
2000	0.6	0.044	4	< 0.01

Because of the insignificant standard model background, for any of these $Y^{\pm\pm}$ masses, detection of events at resonance signals discovery of a new particle.

Summary

Parity violation in weak interactions, chiral fermions and triangle anomalies underly the Standard Model and its extension to the Bilepton Model.

A possible search for ATLAS and CMS is for $Y^{\pm\pm}$ which underly an explanation of three families in the Bilepton Model predicts doubly-charged siblings $Y^{\pm\pm}$ to accompany $W^{\pm}$.

There is the expected mass range

$800GeV \leq M_{Y^{\pm\pm}} \leq 2000GeV$

which renders this new particle accessible to the LHC.

`Thank you for your attention`