Thank for the invitation

DOUBLY-CHARGED BILEPTONS AT THE LARGE HADRON COLLIDER

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Exploring Scalar and Vector Bileptons at the LHC in the 331 Model.
Phys. Lett. **B** (2018, to appear)
`arXiv:1806.04536[hep-ph]`.

Introduction

Because the two most popular theoretical models aiming beyond the standard model - electroweak supersymmetry and large extra dimensions - have received no encouragement from LHC data, in this talk we shall discuss what is the most likely type of BSM particle.

The bilepton model was invented 26 years ago as merely one exemplar of what was expected wrongly to be a large new class of models.

In 2018, either the LHC fails to find any BSM particle or the bilepton model (331-model) is 90% likely to be correct.

e.g. $(2/3) \times 90\% \simeq 60\%$.

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 explicit 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.

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 The one-loop correction was calculated in 1948 independently by Nambu (unpublished) and by Schwinger (epitaph).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 papers by Frank Yang to go 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. Led to twenty NPs.`

T.D. Lee and C.N. Yang,
Question of Parity Conservation in Weak Interactions. Phys. Rev. **104,** 254 (1956).
`personal influence, well-written`

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.  MG-M.`

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`

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 $p \to e^+\pi^0$ by tree-level gauge boson exchange with lifetime

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

However, in 1984 the Irvine-Michigan-Brookhaven Collaboration announced that

$$\tau_p > 10^{32} y$$

which killed the minimal SU(5) GUT theory.

One attempt to accommodate the proton lifetime appeared in
Staying Alive with SU(5)
by Frampton and 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.

After the demise of GUTs came
the first superstring revolution.

Brief digression on supertheories :
supersymmetry, supergravity, superstrings.

No parental relationship to
supersymmetry or supergravity.
Have contributed to superstring theory.

1974 First book on string theory.

`Sales in 1979 and 1986`

1978 Taught Edward Witten string theory.

`Still treats me as his professor`

1983 Hexagon anomaly +T.Kephart.

`First appearance of O(32). LA-G`

1988 P-adic string +Y.Okada

`First physics use of prime numbers`

1988-2018 Supertheories spectator

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 Higgs 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. Probably nobody would consider SU(15) grand unification as a realistic model for proton decay.

Nevertheless, it was by assiduous study of this SU(15) 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 is provided (after $\sim$ 100 tries) by the 3-3-1 or 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 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 $Q = 5/3$.

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

S. Dimopoulos

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

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 <u>exactly three</u>.

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 $\to$ 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 $m_{Y^{\pm\pm}} > 800 GeV$.

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 $m_{Y^{\pm}} > 800 GeV$.

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.
Discussed at CERN their protocols:
Anybody can search without permission.
A talk or paper representing Collaboration
needs permission from ATLAS Spokesperson.

`Fabiola Gianotti`
Email exchanges while at CERN.

CMS

`Jim Virdee`
Discussed stiff muons with four tesla.

`Luke Kreczko`
Presently searching for bileptons
using CMS data in Bristol.
Results eagerly awaited !!!

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 theoretical upper limit

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

which renders this new particle accessible to the LHC.

Thank you for your attention