NEW GAUGE BOSONS
AT THE LHC AND ELSEWHERE

J. Rosner – U. Chicago – 5/8/06 at U. Penn. in honor of Paul Langacker

Thanks to Paul, David London, and Rick Robinett for enjoyable collaborations

Bibliography at end: Paul, Mirjam have been key players from the beginning.

Standard Model extensions in the gauge sector:
SU(5) ⇒ SO(10) ⇒ E_6, motivations and signatures

Standard Model: SU(2)_L × U(1)_Y (electroweak, 1961–71); SU(3)_c (QCD, 1973)

Georgi-Glashow (1974): SU(5) ⊃ SU(3) × SU(2) × U(1)_Y

\[ SU(5) \sim \begin{bmatrix} SU(3) \\ . \\ . \\ SU(2) \end{bmatrix}, \quad U(1)_Y \sim \text{diag}(2, 2, 2, -3, -3) \]

Soon after: SO(10) ⊃ SU(5) × U(1)_x (natural family structure, right-hand neutrino)

Gürsey–Ramond–Sikivie: E_6 ⊃ SO(10) × U(1)_ψ (support from string theory)
SU(5): FEATURES/BUGS

$5^* + 10$ accounts for one family; add 1 for right-handed neutrino $N$

Anomaly cancellation occurs if one chooses $5^* + 10$:

Example: $\sum_f I^f_{3L} Q_f^2 = 0$

True for any 3 gauge bosons

If extending the gauge symmetry: demand new symmetries be anomaly-free

Unification is qualitative (a) unless one introduces supersymmetry (b):
SO(10): THE NEXT STEP

Any SU(N) is contained in SO(2N): exercise in vector-space algebra

SO(10) has a 16-dimensional spinor and its complex conjugate 16*

5* + 10 + 1 of SU(5) = 16 of SO(10) (left-handed quarks and leptons); right-handed quarks and leptons belong to 16*

16: alternate vertices of a 5-dimensional hypercube; 16* occupies the other vertices

Shown here: projection on charge (vertical axis) times color (plane perpendicular to paper)

SO(10) has rank 5 vs. 4 for SU(5): one more U(1)

More freedom in unification; possible new Zs

Represent spinors by \((\pm1/2, \pm1/2, \pm1/2, \pm1/2, \pm1/2)\) with (odd,even) number of + for (16,16*)

\(Q\chi \sim \) scalar product with \((1,1,1,1,1)\)

Spinor techniques: D. London and JLR, PR D 34, 1530 (1986)
SO(10) UNIFICATION

SO(10) has SO(6) \sim SU(4) and SO(4) \sim SU(2)_{L} \times SU(2)_{R} subgroups

SU(4): color group with lepton number as the fourth color; parity violation linked to breaking of SU(2)_{R} at a higher scale than SU(2)_{L}

Examples of multiple SO(10) breaking scales: In (a), SU(2)_{R} \rightarrow U(1)_{R} around 10^{10} \text{ GeV}; in (b), SU(2)_{R} \rightarrow U(1)_{R} near 10^{13} \text{ GeV}.

No proton decay problems; even case (b) gives \tau_p > 10^{37} \text{ y}
**E₆ MULTIPLETS**

E₆ has complex representations (good for P violation), contains SO(10), is not much larger, allows for sterile neutrinos (feature/bug?), and appears in string compactifications from E₈ × E₈.

27-dimensional (fundamental) representation of E₆ contains the 16 as well as a 10 and a 1 of SO(10). The 10 has exotic quarks and leptons; the 1 ("n") is a sterile neutrino candidate.

Interesting U(1) charges are \( Q_X, Q_\psi \), any combinations, e.g., one decoupling from right-hand neutrino: 

\[
Q_N = (Q_X + \sqrt{15} Q_\psi) / 4
\]

<table>
<thead>
<tr>
<th>SO(10)</th>
<th>( N_1 Q_\psi )</th>
<th>SU(5)</th>
<th>( N_2 Q_X )</th>
<th>( N_2 Q_N )</th>
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<tbody>
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<td>1</td>
<td>5*</td>
<td>3</td>
<td>2</td>
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<td>-1</td>
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\( N_{1,2}^{-1} = (2\sqrt{6}, 2\sqrt{10}) \)

\( Q_N(N) = 0 \): can have heavy Majorana \( N \)

not contributing to \( Z_N \) anomaly

Hence \( Z_N \) can be light

Note \( Q_N \leftrightarrow -Q_X \) flips 5* ↔ 5*, 1 ↔ 1.
TESTING FOR $U(1)_{\chi,\psi}$ MIXTURES

Left-handed states:
Standard:
16, 5* : $\bar{d}, e^-, \nu_e$
16, 10 : $u, d, \bar{u}, e^+$
16, 1 : $\bar{N}$ (r.h. neutrino)

Exotic:
10, 5* : $\bar{D}, E^-, \nu_E$
10, 5 : $D, E^+, \bar{\nu}_E$
1, 1 : $n$ (sterile neutrino)

Special cases:
$Z_\psi$ : $\theta = 0^\circ$; $Z_\chi$ : $\theta = 90^\circ$
$Z_N$ : $\theta = \tan^{-1}\sqrt{15} = 75.5^\circ$
$Z_\eta$ : $\theta = 127.8^\circ$
(in some string schemes)

Plus left-right models
$Z'$ in $e^+e^-$ Collisions

Forward-backward asymmetry $\rightarrow$ couplings

$$A_{FB} = \frac{3(R_c^2 - L_c^2)(R_f^2 - L_f^2)}{4(R_e^2 - L_e^2)(R_f^2 - L_f^2)} \text{ is a function of } \theta$$

$$g_1 \equiv L_e = -R_d = \frac{\sin(\theta)}{2 \sqrt{6}} + \frac{3 \cos(\theta)}{2 \sqrt{10}};$$

$$g_2 \equiv -R_e = L_d = L_u = -R_u = \frac{\sin(\theta)}{2 \sqrt{6}} - \frac{\cos(\theta)}{2 \sqrt{10}}.$$  

Simplified picture: Asymmetries at the resonance peak (neglecting $\gamma$, $Z$):

No asymmetry for $e^+e^- \rightarrow u\bar{u}$; $u$ quark couplings purely axial

$\theta = \arctan \sqrt{3/5} \simeq 38^\circ : g_2 = 0$

$\theta = 90^\circ : g_2 = g_1 \text{ (pure axial)}$

$\theta \simeq 113^\circ : g_1 = 0$

$\theta \simeq 142^\circ : g_2 = -g_1 \text{ (vector)}$

In practice interference with $\gamma$, $Z$ is important even near peak.

NLC ($\rightarrow$ ILC) studies indicate sensitivity to $Z'$s well above CM energy
$Z'$ AT THE LHC

ATLAS $Z'$ reach for 100 fb$^{-1}$: CMS $Z'$ reach as function of $\int \mathcal{L} dt$:

While proton-proton collisions are F-B symmetric, asymmetries are still expected, but they are odd in pseudorapidity $\eta$: quarks in protons are faster than antiquarks.

Dilutes diagnostic capability; With 400 fb$^{-1}$ CMS can tell $Z_\chi$ from heavy standard $Z$ or $Z_\psi, Z_\eta$ up to 2.0–2.7 TeV; these last 3 can be told apart only up to 1–1.5 TeV.
EARLY LHC VS TEVATRON

With 30 pb\(^{-1}\) LHC can observe a \(Z_\chi\) with 5\(\sigma\) significance at 1 TeV.

Cross sections vary by a factor of 3 in either direction depending on the \(Z'\).

Each TeV in mass requires a factor of about 10–15 more \(\mathcal{L}dt\).

CDF (hep-ex/0602045) uses \(e^+e^-\) mass and angular distribution:

\[ A_{FB}^{raw} \]

\(\Rightarrow\) Lower limits of \( (860, 735, 725, 745, 710) \) GeV on \( (Z_{SM}, Z_\chi, Z_\psi, Z_\eta, Z_N) \).
SUMMARY

Grand unified theories beyond SU(5), such as SO(10) and E₆, can lead to new neutral gauge bosons whose couplings can be probed, e.g., with forward-backward asymmetries.

Paul has contributed greatly to the theoretical effort in searching for these bosons; we look forward to further results from the Tevatron, LHC, and eventually an ILC.

Have not touched on many other potential sources of new bosons, such as Kaluza-Klein excitations, little Higgs models (for the latter, see G. Azuelos et al., ATLAS note, March 22, 2004).

Extended gauge structures also have implications baryo/leptogenesis, proton decay, and neutrino masses, also subjects for which we owe Paul a great debt of gratitude.

THANK YOU!!!
A PAGE OF BIBLIOGRAPHY

CDF Collaboration, A. Abulencia *et al.*, hep-ex/0602045.