Beyond the Standard Model

*Theoretical perspectives*

**Bogdan Dobrescu (Fermilab)**
$W_L^+ W_L^-$ scattering:

Perturbatively: $\sigma \left( W_L^+ W_L^- \rightarrow W_L^+ W_L^- \right) \approx \frac{G_F^2 s}{16\pi}$

This makes sense only up to $\sqrt{s} \sim 1$ TeV.

(Lee, Quigg, Thacker, 1977)

At higher energy scales:

★ A new particle: Higgs boson

or

★ New strong interaction (perturbative expansion not valid)

or

★ Quantum field theory description breaks down
### Standard Model

**Fermion and scalar gauge charges:**

<table>
<thead>
<tr>
<th></th>
<th>$SU(3)_C$</th>
<th>$SU(2)_W$</th>
<th>$U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>quark doublet:</strong> $q^i_L = (u^i_L, d^i_L)$</td>
<td>3</td>
<td>2</td>
<td>1/3</td>
</tr>
<tr>
<td><strong>right-handed up-type quark:</strong> $u^i_R$</td>
<td>3</td>
<td>1</td>
<td>4/3</td>
</tr>
<tr>
<td><strong>right-handed down-type quark:</strong> $d^i_R$</td>
<td>3</td>
<td>1</td>
<td>−2/3</td>
</tr>
<tr>
<td><strong>lepton doublet:</strong> $l^i_L = (\nu^i_L, e^i_L)$</td>
<td>1</td>
<td>2</td>
<td>−1</td>
</tr>
<tr>
<td><strong>right-handed charged lepton:</strong> $e^i_R$</td>
<td>1</td>
<td>1</td>
<td>−2</td>
</tr>
<tr>
<td><strong>Higgs doublet:</strong> $H$</td>
<td>1</td>
<td>2</td>
<td>+1</td>
</tr>
</tbody>
</table>

$i = 1, 2, 3$ labels the fermion generations.
Gauge symmetries may be broken by quantum effects. Cure: sums over fermion triangle diagrams must vanish.

\[
\text{Standard Model: anomalies cancel within each generation}
\]

\[
[SU(3)]^2 U(1): \quad 2(1/3) + (-4/3) + (2/3) = 0
\]

\[
[SU(2)]^2 U(1): \quad 3(1/3) + (-1) = 0
\]

\[
[U(1)]^3: \quad 3 \left[ 2(1/3)^3 + (-4/3)^3 + (2/3)^3 \right] + 2(-1)^3 + (-2)^3 = 0
\]

\[
U(1)-\text{gravitational: } \quad 2(1/3) + (-4/3) + (2/3) = 0
\]
Could there exist new gauge bosons?

Yes, if they are sufficiently heavy ...

(new gauge symmetry must be spontaneously broken)
Consider an $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_Z$ gauge symmetry spontaneously broken down to $SU(3)_C \times U(1)_{em}$ by the VEVs of a doublet $H$ and an $SU(2)_W$-singlet scalar, $\varphi$.

Three electrically-neutral gauge bosons: $\gamma, Z, Z'$. 

$Z'$ interactions with fermions in the Lagrangian: 

$$ \sum_f (z_f g_z) \bar{f} \gamma^\mu f Z'_\mu $$

“Nonexotic” $Z'$ (Appelquist, Dobrescu, Hopper: hep-ph/0212073)

Assume:

- generation-independent charges,
- quark and lepton masses as in the standard model,
- no new fermions other than an arbitrary number of $\nu_R$'s
Fermion and scalar gauge charges:

<table>
<thead>
<tr>
<th></th>
<th>$SU(3)_C$</th>
<th>$SU(2)_W$</th>
<th>$U(1)_Y$</th>
<th>$U(1)_Z$</th>
</tr>
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<tbody>
<tr>
<td>$q^i_L$</td>
<td>3</td>
<td>2</td>
<td>1/3</td>
<td>$z_q$</td>
</tr>
<tr>
<td>$u^i_R$</td>
<td>3</td>
<td>1</td>
<td>4/3</td>
<td>$z_u$</td>
</tr>
<tr>
<td>$d^i_R$</td>
<td>3</td>
<td>1</td>
<td>$-2/3$</td>
<td>$2z_q - z_u$</td>
</tr>
<tr>
<td>$l^i_L$</td>
<td>1</td>
<td>2</td>
<td>$-1$</td>
<td>$-3z_q$</td>
</tr>
<tr>
<td>$e^i_R$</td>
<td>1</td>
<td>1</td>
<td>$-2$</td>
<td>$-2z_q - z_u$</td>
</tr>
<tr>
<td>$\nu^k_R$, $k = 1, ..., n$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>$z_k$</td>
</tr>
<tr>
<td>$H$</td>
<td>1</td>
<td>2</td>
<td>$+1$</td>
<td>$-z_q + z_u$</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

$[SU(3)_C]^2U(1)_Z$, $[SU(2)_W]^2U(1)_Z$, $U(1)_Y[U(1)_Z]^2$ and $[U(1)_Y]^2U(1)_Z$ anomalies cancel
Gravitational-$U(1)_z$ and $[U(1)_z]^3$

anomaly cancellation conditions:

$$\frac{1}{3} \sum_{k=1}^{n} z_k = -4z_q + z_u$$

$$\left( \sum_{k=1}^{n} z_k \right)^3 = 9 \sum_{k=1}^{n} z_k^3$$

Nontrivial solutions only if the number of $\nu_R$ is $n \geq 3$.

(e.g. $z_1 = z_2 = z_3 = -4z_q + z_u$)

Special case: $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_{B-L}$

Charges given by the baryon minus lepton number:

$$z_q = z_u = z_d = -\frac{z_l}{3} = -\frac{z_e}{3} = -\frac{z_\nu}{3} , \quad z_H = 0$$

no $Z'$-$Z$ mixing at tree level $\Rightarrow$ no strong constraints from electroweak measurements
Z' searches at the Tevatron

CDF Run II Preliminary (448 pb⁻¹)

\[ \chi^2 / \text{dof} = 13.6/13 \]

\[ Z' \to e^+ e^- (M_{Z'}=600 \text{GeV}, g_z=0.2) \]
Z' searches at the Tevatron:
More general charges are allowed in the presence of new fermions:

<table>
<thead>
<tr>
<th></th>
<th>$SU(3)$</th>
<th>$SU(2)$</th>
<th>$U(1)_Y$</th>
<th>$U(1)_{B-xL}$</th>
<th>$U(1)_{q+xu}$</th>
<th>$U(1)_{10+x5}$</th>
<th>$U(1)_{d-xu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_L$</td>
<td>3</td>
<td>2</td>
<td>1/3</td>
<td>1/3</td>
<td>1/3</td>
<td>1/3</td>
<td>0</td>
</tr>
<tr>
<td>$u_R$</td>
<td>3</td>
<td>1</td>
<td>4/3</td>
<td>1/3</td>
<td>$x/3$</td>
<td>$-1/3$</td>
<td>$-x/3$</td>
</tr>
<tr>
<td>$d_R$</td>
<td>3</td>
<td>1</td>
<td>$-2/3$</td>
<td>1/3</td>
<td>$(2-x)/3$</td>
<td>$-x/3$</td>
<td>1/3</td>
</tr>
<tr>
<td>$l_L$</td>
<td>1</td>
<td>2</td>
<td>$-1$</td>
<td>$-x$</td>
<td>$-1$</td>
<td>$x/3$</td>
<td>$(1-x)/3$</td>
</tr>
<tr>
<td>$e_R$</td>
<td>1</td>
<td>1</td>
<td>$-2$</td>
<td>$-x$</td>
<td>$-(2+x)/3$</td>
<td>$-1/3$</td>
<td>$x/3$</td>
</tr>
<tr>
<td>$\nu_R$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>$-1$</td>
<td>$(-4+x)/3$</td>
<td>$(-2+x)/3$</td>
<td>$-x/3$</td>
</tr>
<tr>
<td>$\nu'_R$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>.</td>
<td>.</td>
<td>$-1-x/3$</td>
<td>.</td>
</tr>
<tr>
<td>$\psi^l_L$</td>
<td>1</td>
<td>2</td>
<td>$-1$</td>
<td>$-1$</td>
<td>.</td>
<td>$-(1+x)/3$</td>
<td>$-2x/5$</td>
</tr>
<tr>
<td>$\psi^l_R$</td>
<td>1</td>
<td>2</td>
<td>$-1$</td>
<td>$-x$</td>
<td>.</td>
<td>$2/3$</td>
<td>$(-1+x/5)/3$</td>
</tr>
<tr>
<td>$\psi^e_L$</td>
<td>1</td>
<td>1</td>
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<td>.</td>
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<td>.</td>
</tr>
<tr>
<td>$\psi^d_L$</td>
<td>3</td>
<td>1</td>
<td>$-2/3$</td>
<td>.</td>
<td>.</td>
<td>$-2/3$</td>
<td>$(1-4x/5)/3$</td>
</tr>
<tr>
<td>$\psi^d_R$</td>
<td>3</td>
<td>1</td>
<td>$-2/3$</td>
<td>.</td>
<td>.</td>
<td>$(1+x)/3$</td>
<td>$x/15$</td>
</tr>
</tbody>
</table>
A user-friendly parametrization:

\[
\sigma (p\bar{p} \rightarrow Z'X \rightarrow l^+l^-X) = \frac{\pi}{48s} \left[ c_u w_u \left( \frac{M_{Z'}^2}{s}, M_{Z'} \right) + c_d w_d \left( \frac{M_{Z'}^2}{s}, M_{Z'} \right) \right]
\]

All the information about charges is contained in:

\[
c_{u,d} = g_z^2 \left( z_q^2 + z_{u,d}^2 \right) Br(Z' \rightarrow l^+l^-)
\]
The region above each curve is excluded.

$M = 800 \text{ GeV}/c^2$

$600 \text{ GeV}/c^2$

$400 \text{ GeV}/c^2$

$200 \text{ GeV}/c^2$

$150 \text{ GeV}/c^2$

CDF - preliminary (200 $\mu b^{-1}$) – see Greg Veramendi’s JETP talk on May 13, 2005
10+$\times 5$ models

CDF Run II Preliminary (448 pb$^{-1}$)

Expected $Z'$ Exclusion vs. Measured $Z'$ Exclusion

$Z'$ Mass (GeV/c$^2$) vs. $Z'$ Couplings $X$

$g_z = 0.03$, $g_z = 0.05$, $g_z = 0.10$, $g_z = 0.30$

Carena, Daleo, Dobrescu, Tait, PRD 70, 093009 (2004)
LHC:

$$\sigma(pp \rightarrow Z'X \rightarrow l^+l^-X) = \frac{\pi}{48 s} \left[ c_u w'_u \left( \frac{M^2_{Z'}}{s}, M_{Z'} \right) + c_d w'_d \left( \frac{M^2_{Z'}}{s}, M_{Z'} \right) \right]$$

$w'_u$ and $w'_d$ contain all the information about QCD:
values at the LHC are different than at the Tevatron

$\Rightarrow$ $c_u$ and $c_d$ can be determined independently if a $Z'$ is observed at both the Tevatron and the LHC.

More information about $Z'$ couplings ($U(1)_Z$ charges) can be extracted from angular distributions, etc.
Even when \( z_q = z_u = z_d = z_l = z_e = 0 \)

there can still be interactions of the standard model fields with the new massless gauge boson:

higher-dimensional operators!

A \( \gamma' \) may couple to quarks and leptons via dimension-6 operators suppressed by a scale \( \lesssim 1 \) TeV!

\textit{BD, Phys. Rev. Lett. 94, 151802 (2005)}

Tevatron - “factory” of heavy particles, but also:

\( \gamma' \) production at the Tevatron

\textit{Example: monojet + missing energy}

\begin{center}
\begin{tikzpicture}
\draw[gluon] (0,0) -- (2,0);
\draw[gluon] (2,0) -- (3,1);
\draw[gluon] (3,1) -- (4,0);
\draw[gluon] (4,0) -- (5,1);
\end{tikzpicture}
\end{center}

Tevatron - “factory” of massless particles!
Vector-like quarks

$q_L, q_R$: same gauge charges

$\Rightarrow$ vector-like quarks have gauge invariant masses

unlike all elementary fermions discovered so far!

Predicted in many models:

- "Top-quark seesaw" model (Dobrescu, Hill, 1997)
  $\Rightarrow$ Higgs doublet is composite

- "Little Higgs" models (Arkani-Hamed et al, 2002)
  $\Rightarrow$ no quadratic divergences at 1-loop
“Beautiful mirrors” (Choudhury, Tait, Wagner, 2001)

→ explains $A_{FB}^b$;

→ signal in Run II: $b' \rightarrow bZ$ for $m_{b'} < 300$ GeV

(whole region of parameter space can be explored with 2 fb$^{-1}$)
Fermions in a compact dimension

Lorentz group in 5D ⇒ vector-like fermions: \( \chi = \chi_L + \chi_R \)

Chiral boundary conditions: \( \chi_L(x^\mu, 0) = \chi_L(x^\mu, \pi R) = 0 \)
\[
\frac{\partial}{\partial y} \chi_R(x^\mu, 0) = \frac{\partial}{\partial y} \chi_R(x^\mu, \pi R) = 0
\]

Kaluza-Klein decomposition:
\[
\chi = \frac{1}{\sqrt{\pi R}} \left\{ \chi_R^0(x^\mu) + \sqrt{2} \sum_{j \geq 1} \left[ \chi_R^j(x^\mu) \cos \left( \frac{\pi j y}{L} \right) + \chi_L^j(x^\mu) \sin \left( \frac{\pi j y}{L} \right) \right] \right\}
\]

Kaluza-Klein modes, \( \chi^j(x) \): a tower of massive particles
\[
m_j^2 = m_0^2 + \frac{j^2}{R^2}
\]
Universal Extra Dimensions


All Standard Model particles propagate in $D \geq 5$ dimensions.

Kaluza-Klein modes are states of definite momentum along the compact dimensions.

Momentum conservation $\rightarrow$ KK-number conservation

\[ \mathcal{L}_{4D} = \int dy \mathcal{L}_{5D} \]

At each interaction vertex:

\[ j_1 \pm j_2 \pm \ldots \pm j_n = 0 \text{ for a certain choice of } \pm \]
In particular: $0 \pm \cdots \pm 0 \neq 1$

$\Rightarrow$ tree-level exchange of KK modes does not contribute to currently measurable quantities

$\Rightarrow$ no single KK 1-mode production at colliders

Bounds from one-loop shifts in $W$ and $Z$ masses, and other observables:

$$\frac{1}{R} \gtrsim 300 \text{ GeV}$$

- Pair production of KK 1-modes at colliders:
  cascade decays to $4l + \not{E}_T$ (soft leptons).
Could be discovered soon!

(Cheng, Matchev, Schmaltz, hep-ph/0205314)
At one-loop level: $j_1 \pm j_2 \pm \ldots \pm j_n = \text{even}$

KK parity is conserved: $(-1)^j$

At colliders: $s$-channel production of the 2-modes

Second-level masses: $\sim 2/R$.

Decay into two 1-modes followed by cascade decays (soft leptons, jets and $p_T$).
Lightest KK particle is stable in UED:
$\gamma^{(1)}$ is a viable dark matter candidate
(from Servant, Tait, hep-ph/0206071)

Many other models in extra dimensions:
e.g., “Opaque branes” - localized operators (Carena, Tait, Wagner, et al, 2002)
6D is special...

- Global $SU(2)_W$ anomaly cancellation requires $3 \mod 3$ quark and lepton generations!

- Gravitational anomaly cancellation in 6D requires one right-handed neutrino per generation, and 6D Lorentz symmetry allows $\nu$ masses only of the Dirac type.

- Proton lifetime is sufficiently long
Compactification of two extra dimensions

Chiral boundary conditions on a square
(Dobrescu, Ponton, hep-ph/0401032; work with G. Burdman and E. Ponton)

\[ \Phi(y, 0) = e^{i\theta} \Phi(0, y), \ldots \]
\[ \Rightarrow \theta = n\pi/2 \]

Symmetry: \( Z_8 \times Z_2^{KK} \Rightarrow \) proton stability and dark matter candidate

The (1,1) mode has a mass of \( \sqrt{2}/R \), and has KK parity +

Signals at the Tevatron and LHC:
s-channel production of a (1,1) mode gluon, followed by a cascade decay to \( \gamma^{(1,1)} \) + soft leptons and jets, and \( \gamma^{(1,1)} \rightarrow l^+l^- \) (high \( p_T \) leptons).
Light stop at the Tevatron
Balazs, Carena, Wagner, hep-ph/0403224

\[ \tilde{t} \rightarrow c\tilde{\chi} \]
Conclusions

New physics searches can be done based on:
• a certain signature \((ee, \gamma\gamma, \ldots)\),
• a certain particle \((Z', a\text{ vector-like quark, } \ldots)\),
• a certain model \((\text{MSSM, universal extra dimensions, } \ldots )\).

In all these categories there are new searches that remain to be done!

This is a great time to analyze the CDF and D0 data; we are all excited awaiting to learn what is in there.

*Bogdan Dobrescu (Fermilab)*