Beyond the Standard Model — Bogdan Dobrescu (*Fermilab*)

September 2011 - European School of HEP: *Remnants from Lecture 1:*

Comparison between solutions to the hierarchy problem:

1. Dynamically-broken supersymmetry

Susy breaking scale is exponentially suppressed compared to $M_{\rm Planck}$ *due to gauge dynamics.*

Problem: μ **term (the Higgsino mass) is supersymmetric.**

Why $\mu \sim v$**?** (some solutions exist)

2. Technicolor

Exponential hierarchy between $M_{\rm Planck}$ *and the scale where the technicolor gauge interaction becomes strong.*

Problem: fit to the electroweak data? (some solutions exist)

3. RS1

$1/M_{\rm Planck}$ *is exponentially suppressed compared to* $1/v$.

Solution (?) #5: Large extra dimensions (ADD)

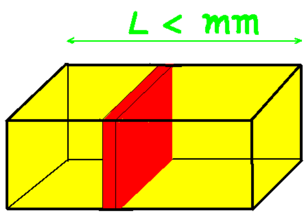
Graviton only in flat extra dimensions

Gravitational interactions measured at distances $\gtrsim$ 10^{-3}cm:

$$F_N = \frac{m_1 m_2}{M^2_{\rm Planck} r^2}$$

We may live on a wall in extra dimensions!

(Arkani-Hamed, Dimopoulos, Dvali, 1998)



Newton's law in extra dimensions: $F_N = \dfrac{m_1 m_2}{(M_s r)^{2+n}}$

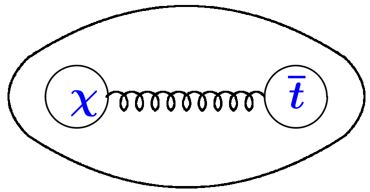
Scale of quantum gravity may be as low as $\sim$ 10 TeV: $M_s = \left(\dfrac{M^2_{\rm Planck}}{L^n}\right)^{1/(2+n)}$

Solution #4: Composite Higgs models

Higgs boson is a bound state of top quark with a new quark χ.

"Top seesaw model" *(Chivukula et al, hep-ph/9809470)*

Binding may be due to some strongly-interacting heavy gauge bosons

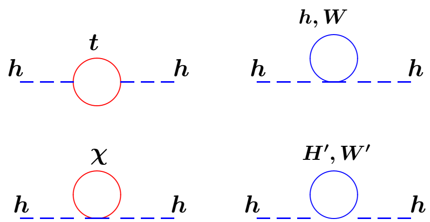


Scale of Higgs compositeness may be as low as a few TeV.

Homework 1.5: *What are the quantum numbers of χ? How would you search for this hypothetical particle?*

(Partial) Solution #6: Little Higgs

1-loop quadratic divergences cancelled by partners carrying the same spin. *(Arkani-Hamed et al, hep-ph/0206021)*



Effective theory valid up to scales of order ~ 5 TeV, where some unspecified new dynamics takes over.

(Partial) Solution #7: Twin Higgs

Z. Chacko, H. S. Goh and R. Harnik, hep-ph/0506256

1-loop quadratic divergences are cancelled if there is a parity which interchanges each SM particle with a new particle that transforms under a twin SM gauge group.

If the new particles are neutral under the SM gauge group, than these partners would be very hard to see at the LHC .

This is unlike all other known solutions, where a $\tilde{t}$ squark or a χ quark or something else is visible at the TeV scale.

Effective theory valid again only up to scales of order ~ 5 TeV...

Beyond the Standard Model

Lecture 2

Bogdan Dobrescu (*Fermilab*)

Outline:

- *Electroweak symmetry breaking (Lecture 1)*
- **Quark and lepton masses; vectorlike quarks (Lecture 2)**
- *New gauge bosons (Lecture 3)*
- *WIMPs and cascade decays (Lecture 4)*
- *How to search for new phenomena (Lecture 5)*

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Elementary particles "observed" in experiments:

$$\left.\begin{array}{l} \text{leptons} \left\{ \begin{array}{ccc} \begin{pmatrix} \nu_L^e \\ e_L \end{pmatrix} & \begin{pmatrix} \nu_L^\mu \\ \mu_L \end{pmatrix} & \begin{pmatrix} \nu_L^\tau \\ \tau_L \end{pmatrix} \\ e_R & \mu_R & \tau_R \end{array} \right. \\ \\ \text{quarks} \left\{ \begin{array}{ccc} \begin{pmatrix} u_L \\ d_L \end{pmatrix} & \begin{pmatrix} c_L \\ s_L \end{pmatrix} & \begin{pmatrix} t_L \\ b_L \end{pmatrix} \\ u_R & c_R & t_R \\ d_R & s_R & b_R \end{array} \right. \end{array} \right\rangle \text{(spin 1/2)}$$

$$\underbrace{SU(3)}_{\text{8 gluons}} \times SU(2) \times U(1) \text{ gauge bosons} \quad \text{(spin 1)}$$

$$+ \; W, Z, \gamma$$

Fermion masses

All Standard Model fermions are chiral.

The two top quarks:

- **"left-handed" top** *(feels the weak interaction)*
- **"right-handed" top** *(no interaction with $W^\pm$)*

$$\begin{pmatrix} t_L \\ b_L \end{pmatrix} \qquad\qquad \left(t_R \right)$$

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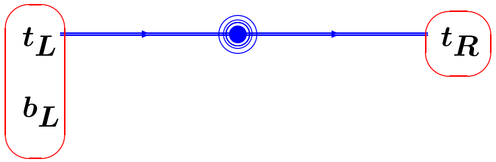
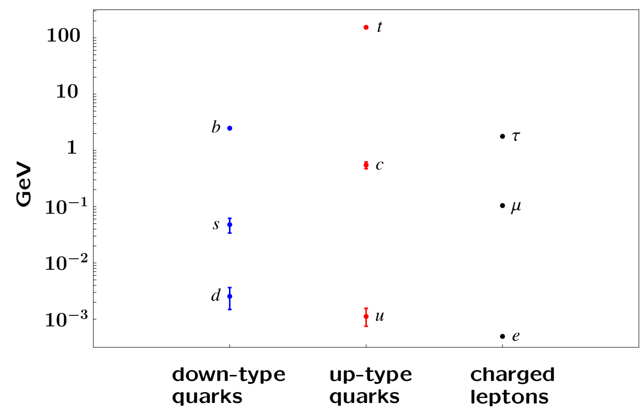
Top mass: t_L turns into t_R and vice-versa



Quark and lepton masses at the 1 TeV scale:



How is electroweak symmetry breaking communicated to fermions?

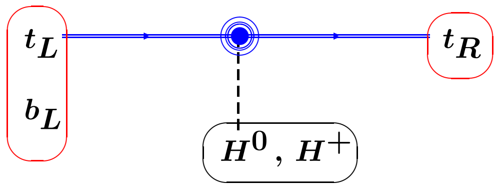
Fermion masses

All Standard Model fermions are chiral.

Top quark gets a mass from its interaction with the vacuum:

$\lambda_t \, \bar{t}_R \langle H^0 \rangle t_L$, $\qquad \langle H^0 \rangle \approx 174$ **GeV**

Measured top mass $\Rightarrow$ coupling constant is $\lambda_t \approx 1$.



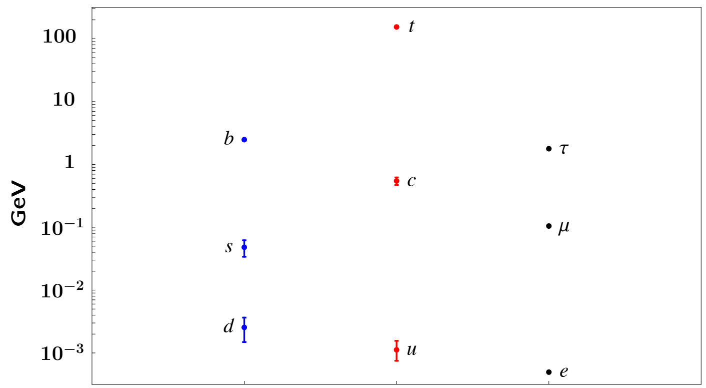
Many attempts at explaining the hierarchy of Yukawa couplings:

- **discrete symmetries $\rightarrow (\langle \phi \rangle / M)^n$ suppressions.**
- **GUT relations.**
- **wave function overlaps in extra dimensions.**
- **...**
- **loop suppressions:**

Georgi, Glashow, 1972 – **attempts to calculate the electron mass as a one loop contribution involving the muon mass.**

Many papers in the 1980's (*e.g., Balakrishna, Kagan, Mohapatra, 1988*)

Typical scheme: *3rd generation masses at tree level,*
2nd generation masses at one loop,
1st generation masses at two loops.



Let us assume that only the top quark gets its mass at tree level, $y_t \, \bar{t}_R Q_L^3 \, H$, and introduce some interactions that communicate EWSB to the other quarks and leptons.

Case study 2: A scalar leptoquark

B.D, P. Fox, 0805.0822

r: scalar field transforming as (3,2,+7/6) under $SU(3)_c \times SU(2)_W \times U(1)_Y$

$$r = \begin{pmatrix} r_u \\ r_d \end{pmatrix} \quad \begin{matrix} \text{charge} + 5/3 \\ \text{charge} + 2/3 \end{matrix}$$

Most general renormalizable interactions with SM fermions

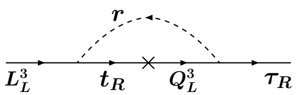
$$\lambda_{ij} \, r \, \overline{u}_R^i L_L^j + \lambda'_{ij} \, r \, \overline{Q}_L^i e_R^j \qquad (r \text{ is a leptoquark})$$

$i, j = 1, 2, 3$ label the fermion generations:

$$L^1 = \begin{pmatrix} \nu_e \\ e \end{pmatrix} \; , \; L^2 = \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \; , \; \ldots$$

In the absence of masses, the identity of fermion generations is ill defined.

The one-loop diagram responsible for the tau mass:



Only one linear combination of L_L^j couples to t_R
$\Rightarrow m_\mu = m_e = 0$ at 1-loop

Only one linear combination of e_R^j couples to Q_L^3

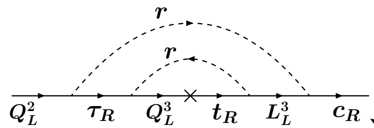
$$m_\tau \simeq \lambda_{33} \lambda'_{33} \, m_t \frac{N_c}{16\pi^2} \ln \left(\frac{\Lambda^2}{M_r^2} \right)$$

Some new physics cuts off the loop integral at a scale Λ:

a superpartner of r, or some dynamics if r is a composite particle, or some particle integrated out to generate the Yukawa couplings of r.

m_τ depends on $\frac{\Lambda}{M_r}$ (only a lower limit on M_r is set by phenomenology).

Charm mass induced by a two-loop "rainbow" diagram:



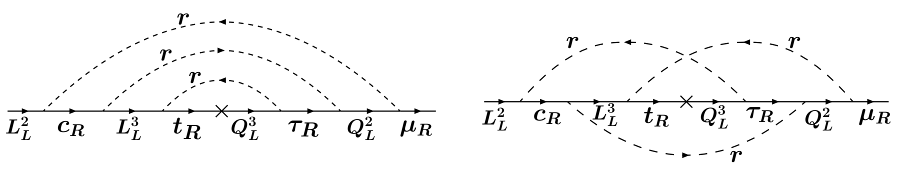
Only one linear combination of Q_L^1 and Q_L^2 couples to $\tau_R \Rightarrow m_u = 0$ at 1-loop

Only one linear combination of u_R^1 and u_R^2 couples to L_L^3

$$m_c \simeq \lambda'_{23} \lambda_{23} \, m_\tau \frac{1}{16\pi^2} \ln \left(\frac{\Lambda^2}{M_r^2} \right)$$

If there are no other contributions to m_c, the m_c/m_τ ratio at 1 TeV requires $\lambda_{23}\lambda'_{23} \approx (3.3)^2$ for $\Lambda \approx 10 M_r$.

Muon mass induced by 3-loop "rainbow" and nonplanar diagrams:

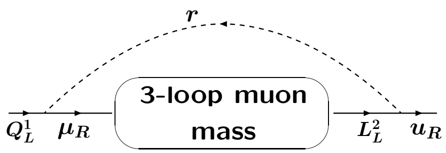


$$m_\mu \simeq \lambda'_{22}\lambda_{22}\, m_c\, [1 + O(1/N_c)]\, \frac{N_c}{16\pi^2} \ln\left(\frac{\Lambda^2}{M_r^2}\right)$$

m_μ/m_c ratio requires $\lambda_{22}\lambda'_{22}\,[1 + O(1/N_c)] \approx (1.5)^2$

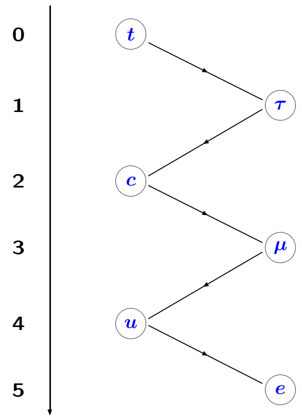
At 3-loops the electron is still massless!

Up-quark mass induced at 4-loops:



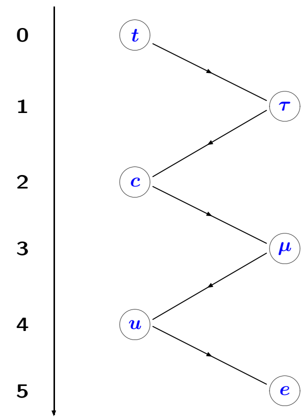
$$m_u \simeq \lambda'_{12}\lambda_{12}\, m_\mu\, \frac{1}{16\pi^2} \ln\left(\frac{\Lambda^2}{M_r^2}\right)$$

Correct m_u/m_μ ratio requires $\lambda_{12}\lambda'_{12} \approx (0.6)^2$



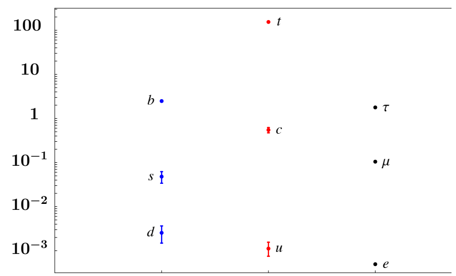
Loop-level where mass is generated

"Domino" mechanism



Loop-level where mass is generated

"Domino" mechanism



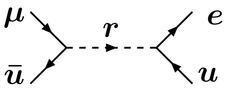
Only input: $\lambda_{ij}\, r\, \overline{u}_R^i L_L^j + \lambda'_{ij}\, r\, \overline{Q}_L^i e_R^j$ and m_t.

$$\lambda \sim \lambda' \sim \begin{pmatrix} 2.3 & 0.6 & 0 \\ 0 & 1.5 & 3.3 \\ 0 & 0 & 0.4 \end{pmatrix}$$

Phenomenological constraints on the r leptoquark:

Tree level flavor-changing processes induced by r exchange:

$\mu \to e$ conversion



$K^+ \to \pi^0 \mu^+ e^-$, ...

$\tau^+ \to K^0 e^+$, ...

$\pi^+ \to e^+ \nu$ versus $\pi^+ \to \mu^+ \nu$

...

Homework 2.1: *draw the Feynman diagrams for these processes. Estimate the coefficients of the 4-fermion effective operators induced by integrating r out.*

$\Rightarrow \quad M_r > O(5 - 50)$ TeV.

Origin of quark and lepton masses may be probed through low energy flavor-changing processes (and could be hidden in high p_T processes).

The hierarchy problem, and the pattern of quark and lepton masses, suggest the existence of structures beyond the SM.

However, there might be novel phenomena that are not related to these.

Let's not search only under the lamppost ...

What kind of new particles may exist?

Vectorlike fermions

A 4th generation of chiral fermions may exist, but there are strong constraints on it from electroweak measurements and also from flavor processes.

Vectorlike (*i.e.* non-chiral) fermions may also exist. Their masses are allowed by the $SU(3)_c \times SU(2)_W \times U(1)_Y$ gauge symmetry,
$\Rightarrow$ may naturally be heavier than the t quark.

Vectorlike fermions are the simplest spin-1/2 particles, and would be a novel form of matter.

Case study 3: A vectorlike t' quark

A vectorlike quark χ which transforms as (3,1,+2/3) under $SU(3)_c \times SU(2)_W \times U(1)_Y$ would mix with the top quark:

$$\mathcal{L} = -\left(\overline{u}^3_L \ , \ \overline{\chi}_L\right) \begin{pmatrix} \lambda_t v_H & 0 \\ M_0 & M_\chi \end{pmatrix} \begin{pmatrix} u^3_R \\ \chi_R \end{pmatrix}$$

$v_H \simeq 174$ GeV is the Higgs vacuum expectation value
λ_t is the top Yukawa coupling
M_0 and M_χ are mass parameters

χ is present in: Top-quark seesaw theory, Little Higgs models, ...

Transform the gauge eigenstates u^3 and χ to the physical states t (discovered at the Tevatron) and t' (remains to be discovered):

$$\begin{pmatrix} t_L \\ t'_L \end{pmatrix} = \begin{pmatrix} \cos\theta_L & -\sin\theta_L \\ \sin\theta_L & \cos\theta_L \end{pmatrix} \begin{pmatrix} u^3_L \\ \chi_L \end{pmatrix}$$

The three initial parameters λ_t, M_0, M_χ are replaced by physical parameters: m_t (measured!), $m_{t'}$ and $s_L \equiv \sin\theta_L$.

Homework 2.2: *Express s_L in terms of λ_t and $m_{t'}$.*
Show that for $m_{t'} \to \infty$, the mixing vanishes ($s_L \to 0$), so that the new physics decouples from the standard model.

Interactions of left-handed quarks with W and Z:

$$t_L - \overline{b}_L - W^+_\mu \;:\; i\frac{g}{\sqrt{2}} c_L\,\gamma_\mu \;\Rightarrow\; s_L < 0.67 \;\text{(from single top production)}$$

$$t'_L - \overline{b}_L - W^+_\mu \;:\; i\frac{g}{\sqrt{2}} s_L\,\gamma_\mu$$

$$t_L - \overline{t}_L - Z_\mu \;:\; i\frac{g}{\cos\theta_W}\left(\frac{1}{2}c_L^2 - \frac{2}{3}\sin^2\theta_W\right)\gamma_\mu$$

$$t_L - \overline{t'}_L - Z_\mu \;:\; i\frac{g}{\cos\theta_W}\frac{1}{2} s_L c_L\,\gamma_\mu$$

$$t'_L - \overline{t'}_L - Z_\mu \;:\; i\frac{g}{\cos\theta_W}\left(\frac{1}{2}s_L^2 - \frac{2}{3}\sin^2\theta_W\right)\gamma_\mu$$

Interactions of t_R, t'_R with the Z are identical with those of the SM t_R.

Interactions with the Higgs boson:

$$\frac{-1}{v_H\sqrt{2}} h^0 \left(c_L^2 m_t\,\overline{t}_L t_R + s_L^2 m_{t'}\,\overline{t'}_L t'_R + c_L s_L m_{t'}\,\overline{t}_L t'_R + c_L s_L m_t\,\overline{t'}_L t_R\right) + \text{H.c.}$$

Decay widths of t':

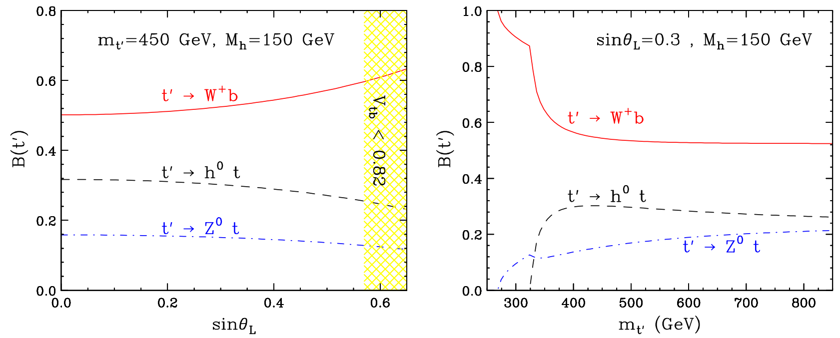
$$\Gamma(t' \to W^+ b) = \frac{s_L^2\, m_{t'}^3}{32\pi v_H^2}\left(1 - \frac{M_W^2}{m_{t'}^2}\right)^2\left(1 + \frac{2M_W^2}{m_{t'}^2}\right)$$

$$\Gamma(t' \to Zt) = \frac{s_L^2 c_L^2\, m_{t'}^3}{64\pi v_H^2}\left[1 + O\left(\frac{M_Z^4}{m_{t'}^4}\right)\right]$$

If $m_{t'} > M_h + m_t$:

$$\Gamma(t' \to ht) = \frac{s_L^2 c_L^2 m_{t'}^3}{64\pi v_H^2}\left[\left(1 + \frac{m_t^2 - M_h^2}{m_{t'}^2}\right)\left(1 + \frac{m_t^2}{m_{t'}^2}\right) + \frac{4m_t^2}{m_{t'}^2}\right]\left[\left(1 - \frac{m_t^2 + M_h^2}{m_{t'}^2}\right)^2 - 4\frac{m_t^2}{m_{t'}^2}\right]^{1/2}$$

Branching fractions of t':



Homework 2.3:

Compute the branching fractions of t' in the $m_{t'} \gg M_h + m_t$ limit.

Homework 2.4:

Analyze a similar theory where there is a vectorlike quark transforming as (3,2,+1/6) under $SU(3)_c \times SU(2)_W \times U(1)_Y$.

QCD production of $t'\bar{t}'$ pairs, followed by t' decays, leads to various final states:

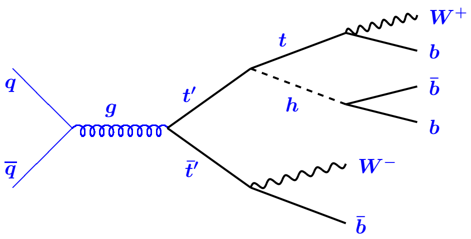
$(W^+b)(W^-\bar{b})$

$(Zt)(W^-\bar{b})$ or $(Z\bar{t})(W^+b)$

$(ht)(W^-\bar{b})$ or $(h\bar{t})(W^+b)$, with $h \to b\bar{b}$ or $h \to W^+W^-$

...

Example:



The Higgs boson could be discovered in the $W^+W^-{+}4b$ sample...

Usual "t' search":