Why the Top Quark?

• Did it have to be there?
• Did it have to be heavy?
• Why is it important?
• What is its role?
A Model of Leptons (1967)

- Group $SU(2) \times U(1)$; gauge bosons $(W^\pm, W^0)$, $B$

- Gauge couplings $g$, $g'$: $\tan \theta_W \equiv g'/g$; $e = g \sin \theta_W$

\[
\left( \begin{array}{c}
\nu_e \\
\nu_\mu
\end{array} \right)_L \left( \begin{array}{c}
\nu_\mu \\
\nu_e
\end{array} \right)_L \quad \left( \begin{array}{c}
e^- \\
\mu^-
\end{array} \right)_L \quad \left( \begin{array}{c}
e_R^- \\
\mu_R^-
\end{array} \right)_L
\]

doublets

singlets

\[
W^i_\mu \rightarrow -ig_2 \sigma^i \gamma_\mu \left( \frac{1-\gamma_5}{2} \right)
\]

\[
B_\mu \rightarrow -ig' y_\gamma \gamma_\mu \left( \frac{1+\gamma_5}{2} \right)
\]
• Cabibbo mixing of $d_L - s_L$ needed by charged current

$$
\begin{pmatrix}
  u \\
  d' \equiv d \cos \theta_c + s \sin \theta_c
\end{pmatrix}_L \quad s'_L = -d_L \sin \theta_c + s_L \cos \theta_c
$$

$$u_R \quad d_R \quad s_R$$

• Flavor changing neutral current transitions predicted, not observed

$$J^\mu_Z = \bar{u}_L \gamma^\mu u_L - \bar{d}'_L \gamma^\mu d'_L - 2\sin^2 \theta_W J^\mu_\bar{Q}
$$

$$= \bar{u}_L \gamma^\mu u_L - \cos^2 \theta_c \ \bar{d}_L \gamma^\mu d_L - \sin^2 \theta_c \ \bar{s}_L \gamma^\mu s_L
$$

$$- \cos \theta_c \sin \theta_c \left( \bar{d}_L \gamma^\mu s_L + \bar{s}_L \gamma^\mu d_L \right) - 2\sin^2 \theta_W J^\mu_Q$$
• **GIM (1970): Introduce fourth \((c)\) quark**
  
  - Quarks and leptons treated symmetrically (up to \(\nu_R\))
  - \(d_L\) and \(s_L\) both in doublets \(\rightarrow\) no tree-level FCNC
  - FCNC loops calculable: \(m_{K_L} - m_{K_S} \rightarrow m_c \sim \) few GeV
  - No triangle anomalies
  - *But*, strong resistance to introducing new particle (cf. Pauli)
The $J/\psi$

- $J/\psi$ ($c\bar{c}$) discovered 1974 at Brookhaven and SLAC
  ($m_c \sim 1.5$ GeV)

- Role of hadron, $e^+e^-$, precision, theory
The Third Generation

$\tau$ lepton, SLAC (1975)  
$(m_\tau \sim 1.8 \text{ GeV})$

$\Upsilon(b\bar{b})$, Fermilab (1976)  
$(m_b \sim 5 \text{ GeV})$
Sequential or Alternative?

- Simplest interpretation: sequential family

\[
\begin{pmatrix}
\nu_	au \\
\tau^-
\end{pmatrix}_L \quad \begin{pmatrix}
t \\
b
\end{pmatrix}_L \quad \tau^-_R \quad t_R \quad b_R
\]

- This is the obvious generalization
- Anomaly cancellation preserved
- Allows CP violation
Other Possibilities

- However, third family could be different (e.g., string constructions)

- Many other ways to cancel anomalies

  - Mirror family: \( \tau^-_L \ t_L \ b_L \ \left( \begin{array}{c} \nu_\tau \\ \tau^- \end{array} \right)_R \ \left( \begin{array}{c} t \\ b \end{array} \right)_R \)

  - Singlet vector: \( \tau^-_L \ b_L \ \tau^-_R \ b_R \) (topless)

  - Doublet vector: \( \left( \begin{array}{c} \nu_\tau \\ \tau^- \end{array} \right)_L \ \left( \begin{array}{c} t \\ b \end{array} \right)_L \ \left( \begin{array}{c} \nu_\tau \\ \tau^- \end{array} \right)_R \ \left( \begin{array}{c} t \\ b \end{array} \right)_R \)

  - Other, more complicated, possibilities
The $\nu_\tau$

- Weak interactions of $\tau$ (lifetime, decay distribution, $A_{FB}^{\tau}$, absence of FCNC $\tau \rightarrow l_1 l_2 \bar{l}_2$) established sequential $\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \tau_R$

- DONUT experiment (Fermilab, 2000) observed $\nu_\tau$ directly

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The Weak Interactions of the $b$

- $e^+e^- \rightarrow b\,\bar{b}$ (full strength interaction)
  - Jade (DESY, 1988): $A_{FB}^b(35 \text{ GeV}) \rightarrow t_{3L}^b - t_{3R}^b = -0.54 \pm 0.15$
    (sequential: $-\frac{1}{2}$; mirror: $+\frac{1}{2}$; singlet or doublet vector: 0)
  - LEP (1992): $\Gamma_b/\Gamma_{had}$ and $A_{FB}^b(M_Z)$; LEP + SLC (2005)

- CLEO (1987): absence of FCNC $B \rightarrow l^+l^-X$ (but reduced strength)

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Top Loops

- Quadratic $G_F m_t^2$ dependence in gauge self-energies breaks $SU(2)$
  ($M_W, Z$, widths, NC/CC)

- Also $Z \rightarrow b\bar{b}$ vertex
  ($\Gamma_Z^b$, $A_{FB}^b$)
Precision Constraints on $m_t$

- **Theory, 1977**

- **1980 global analysis**: $m_L < 500$ GeV ($\rightarrow m_t < 290$ GeV)

- **1987**: $m_t < (175, 180, 200)$ GeV at 90% cl (for $M_H = (10, 100, 1000)$ GeV)

- **1989**: Precise $M_Z$ (Mark II at SLC) and $M_{W,Z}$ (CDF): $m_t = 140^{+43}_{-52}$ GeV for $M_H = 100$ ($\rightarrow 128$ (165) for $M_H = 10$ (1000) GeV)
The LEP, SLD Era, and the Tevatron

- Two loop $m_t - M_H$ and $m_t - \alpha_s$ effects

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A House of Cards?

- Possible weak links in indirect precision predictions
  - Global analysis; unexpected systematics/correlations
  - Gauge principle, group, representations
    (well tested by $W, Z$; fermion couplings)
  - Renormalization of spontaneously broken non-abelian gauge theories, including anomalies and mixed QCD-electroweak ($\mu, \beta$ decay)
  - A heavy Higgs (but $Z \to b\bar{b}$)
  - New $SU(2)$-breaking physics to compensate $m_t$
    ($Z - Z'$ mixing, Higgs triplets)
  - Physics beyond the standard model affecting observables
The lynchpin of the standard theory!

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Why is the $t$ Important?

- Established standard theory at loop level
- Signal and background for new physics
- Top properties, decays as probe of new physics
- **Higgs machine** ($gg$ fusion, $t\bar{t}H$, etc.)
- **Critical parameter** (unitarity triangle, Higgs expectation in MSSM, precision constraint on Higgs mass)
The Standard Model (or decoupled MSSM) Higgs

Present

Future

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**Expectation in MSSM**

- **Bound weakened in extensions of MSSM**

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What is the Role of Top?

- CP violation allowed in CKM matrix
- The top may be the only normal fermion
- The third family may be different (e.g., strings, top-color)
- May drive electroweak symmetry breaking (e.g., radiative breaking in MSSM, top-color)
Radiative Electroweak Symmetry Breaking

- $m_H^2 > 0$ at Planck scale driven negative by large top Yukawa
Conclusions

- Discovery was splendid achievement (experiments and accelerator)
- Critical for establishment of standard theory at quantum level
- Cooperation of discovery machines, precision, theory
- On to the Higgs (or alternative) and beyond
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Congratulations!