What we need to know about Top and why

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Inspirational Message
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Major milestones in particle physics

1970s particle zoo understood:  
  $u, d, s$ bound states

1974 charm discovered

1975 $\tau^{\pm}$ discovered – 3rd generation lepton

1978 bottom discovered – 3rd gen. quark;  
  up–type partner (top) hypothesized

1979 gluon discovered:  
  $SU(3)$ of QCD becomes rock–solid

1983 $W^{\pm}, Z$ discovered:  
  strong belief in $SU(2)_L$ established

1990 LEP data supports 3 neutrinos (gen.’s)

1995 top quark candidate discovered

1990s LEP $e^+e^- \rightarrow W^+W^-$ confirmation of  
  $SU(2)_L$ gauge theory

2000 $\nu_\tau$ discovered (*yawn*)
→ Reinforces Standard Model gauge theory of all forces except gravity:

\[ \text{SU}(3)_c \otimes \text{SU}(2)_L \otimes \text{U}(1)_Y \]

(strong, weak, EM)

Matter particles we see in nature:

\[
\begin{align*}
  (u_d)_L & \quad u_R & \quad d_R & \quad (\nu_e)_L & \quad e_R \\
  (c_s)_L & \quad c_R & \quad s_R & \quad (\nu_\mu)_L & \quad \mu_R \\
  (t_b)_L & \quad t_R & \quad b_R & \quad (\nu_\tau)_L & \quad \tau_R
\end{align*}
\]

Note that we have to have 3 generations to have CP violation!

Top candidate is abnormally heavy, but otherwise looks like SM top quark:

• \( \sigma_{t\bar{t}} \) is right size for QCD production

• \( \text{BR}(t \rightarrow w^+ + b) \sim 1 \) is expected weak decay

\[ Q = +\frac{2}{3} \text{ or } -\frac{4}{3}, \] but not determined
$Q_t$ meas’m’t at LHC – no surprises expected

So why study top in more detail?

1. **top is background to NP @ LHC**
   model it well!

2. **top is SM-like, but not well-measured**
   $g_{\gamma tt}, g_{Ztt}, g_{Wtb}, V_{tb}$ not known!

3. **top can be a window to NP**
   2HDMs, SUSY, Little Higgs, Topcolor, flavor, …

1,2,3 are related, but different aspects
Modeling top

- **corrections to** $\sigma_{t\bar{t}}$:  
  \[ NLO+NLL+[NNLO+NNLL] \sim +40\%, \]  
  but uncertainty $\sim 5 - 20\%$! (exp. $< 10\%$)  
  $\rightarrow$ need full NNLO+NNLL

- **$\sigma_{t\bar{t}+\text{jets}}$:** add’tl hard partons  
  dominant bkg to Higgs, other searches  
  Pythia/Herwig give wrong (low) rates!  
  LO matrix elements IR unsafe –  
  simple matching possible, not rigorous  
  also: $t \rightarrow Wb\bar{j}$ needs proper matching

- **off-shell top production:**  
  difficult, crucial issue at LHC for  
  $H \rightarrow W^+W^- \rightarrow \ell^+\ell^- + X$

- **$t\bar{t}$ spin correlations:**  
  \[
  \frac{1}{\sigma} d^2\sigma \frac{d^2\sigma}{d(\cos\theta_i)d(\cos\theta_{\bar{i}})} = \frac{1}{4}(1 - C\alpha_i\alpha_{\bar{i}} \cos\theta_i \cos\theta_{\bar{i}}) 
  \]  
  $C_{NLO}$ important, depends on spin basis

$\rightarrow$ theor. unc. $\geq$ exp. unc. in all cases!  
(similar issues for single-top production)
Top properties - SM?

→ $\sigma_{tt\bar{t}}$ suggests $g_{gtt} = g_s$ (t is color triplet)
  QCD anom. coups tough at Tev2, LHC

→ $g_{\gamma tt}$, $g_{Ztt}$ essentially unprobed
  must measure $t\bar{t}Z, t\bar{t}\gamma$ rates

→ $g_{Wtb}$ roughly limited from $\text{BR}(t \rightarrow wb) \sim 1$
  and lack of single-top so far
  CLEO $b \rightarrow s\gamma$ data more constraining

→ $\Gamma_t$ (lifetime): involves $g_{Wtb}$ and $V_{tb}$
  only indirectly at Tev/LHC (and tough)
  directly via threshold fit at LC!

→ Yukawa coupling: $Y_t \approx 1$?
  direct meas’mt via $t\bar{t}H$ production
  confirm spont. sym. breaking gen.’s $m_f$

→ $t\bar{t}$ spin correlation:
  $S = \frac{1}{2}$, $\tau_t$ too short to hadronize, $|V_{tb}| > 0.03$

→ charge ($Q_t$) ($Q_t = -4/3$ is exotic, not likely)
  need LHC to confirm w/ $t\bar{t}\gamma$ production
  or lucky $t \rightarrow b\ell\nu$ events @ Tev2 w/ $Q_b$
Type II 2HDMs (incl. SUSY)

→ driven by parameters $M_A$ and $\tan \beta$, ratio of up/down vevs $v_2, v_1$

(small or large $\tan \beta$ preferred, $\sim 3$ or $\sim 30$)

Five physical states:

• $h, H$  CP-even, typically one is SM-like
  mixing of states parameterized by $\alpha$
• $A$  CP-odd, typically degenerate w/ $H$
• $H^\pm$  typically degenerate w/ $H, A$

$t \rightarrow H^+b$ non-trivial if kinem. allowed

t$\bar{t}\phi$ ($\phi = h, H, A$) production possible, unless $\phi$ heavy

\[ G_{tth} \propto \frac{\cos \alpha}{\sin \beta} = \sin(\beta - \alpha) + \frac{1}{\tan \beta} \cos(\beta - \alpha) \]

\[ G_{ttH} \propto \frac{\sin \alpha}{\sin \beta} = \cos(\beta - \alpha) - \frac{1}{\tan \beta} \sin(\beta - \alpha) \]

\[ G_{ttA} \propto \cot \beta \]

(may be difficult to observe...)
**SUSY decays of top**

In addition to $t \rightarrow H^+ b$, top can decay to SUSY pairs ($\mathcal{R}$-parity conserving) or SUSY/SM mixed pairs ($\mathcal{R}$-parity violating).

→ $\mathcal{R}$-parity conserved: SUSY pairs only

$t \rightarrow \tilde{t} \tilde{g} \quad \mathcal{O}(1)$

$t \rightarrow \tilde{b} \chi_1^+ \quad \mathcal{O}(1)$

$t \rightarrow \tilde{t} \chi_1^0 \quad \mathcal{O}(1)$

where kinematically accessible

(light $\tilde{t}, \tilde{b}$ perhaps not so likely)

→ $\mathcal{R}$-parity violated: tree-level

e.g. $t \rightarrow \tilde{\tau} b \rightarrow \tau b \tilde{\chi}_1^0$

→ $\mathcal{R}$-parity violated: 1-loop

$t \rightarrow c \tilde{\nu} \quad BR \sim 10^{-3}$

→ loop-induced FCNC decays

$t \rightarrow c g \quad BR \sim 10^{-3}$

$t \rightarrow c \gamma \quad BR \sim 10^{-5}$

$t \rightarrow c Z \quad BR \sim 10^{-4}$

$t \rightarrow c h \quad BR \sim 10^{-4}$
**Little Higgs models**

**Motivation:**

- precision data constrains new flavor physics to $f \sim 10$ TeV: Little Heirarchy
- solve the SM Higgs sector Big Heirarchy problem by postponing it to $f$

**Basic idea:** some large gauge group broken down at scale $f \sim 1 - 10$ TeV to SM

**minimal new content:**

$$h, \pi, \pi', \pi^\pm, \pi^{\pm\pm}, T, Z', W'^\pm$$

next to minimal is 2HDM: add $H, A, H^\pm$

(elaborate) new gauge structure cancels quadratic divergence to one-loop order - new physics cutoff @ $f \sim 10$ TeV scale
Little Higgs phenomenology

Begin with $SU(5)$ Yukawa Lagrangian:

$$\mathcal{L}_Y = -\lambda_1 f \bar{t}_R \text{Tr}[\Xi^*(iT_2^2)\Xi^*\hat{\chi}_L] - \lambda_2 f \bar{T}_L T_R + h.c.$$  

where $\hat{\chi}_L$ is 5x5 matrix containing $t_L,b_L,T_L$  

t and T mixtures of chiral $t_3$ & vector-like $\bar{t}$:

$$\sin_L = s_L \simeq \frac{\lambda_1 m_t}{\lambda_2 m_T}$$

$T$ too heavy? Check SM top observables:

1. CKM not unitary:

$$V_{tb} = c_L V_{tb}^{SM}, \quad V_{Tb} = s_L V_{Tb}^{SM}$$

2. modified FFV couplings:

$$W^\mu \bar{t}_L b_L \frac{ig}{\sqrt{2}} \left[1 - \left(\frac{v^2}{f^2}\right)\frac{1}{2}(x_L^2 + c^2(c^2 - s^2))\right] \gamma^\mu V_{tb}^{SM}$$

$$W^\mu \bar{T}_L b_L \frac{g}{\sqrt{2}} (\frac{v}{f}) x_L \gamma^\mu V_{tb}^{SM}$$

$$\gamma \bar{t} t \quad eQ_t \text{ (unaffected)}$$

$$\gamma \bar{T} t \quad 0$$

$$\gamma \bar{T} T \quad 0$$

$$Z \bar{t} t \quad \text{really complicated...}$$

3. modified Yukawa couplings as well
Viable strong dynamics model: Topcolor

$\rightarrow 3^{rd}$ generation is special:

$SU(3)_h \otimes SU(3)_l \otimes U(1)_h \otimes U(1)_l \otimes SU(2)_L$

Breaks down to SM + extra $U(1)$ (find $Z'$!)

Eff. 2HDM: $H_{TC2}, H_{ETC} + "top\text{-}pion\"$ triplet

top decays $t \rightarrow \pi^+ b$ also possible

Expect to see rare FCNC top decays:

$t \rightarrow c\gamma, cZ, cg$

Expect FCNC single-top production:

$pp \rightarrow t\bar{c}, tg, etc.$

$Zt\bar{t}$ coupling non-SM due to $Z, Z'$ mixing
Summary

• EW data/theory require $t$, partner of $b$

• We believe this $m = 175$ GeV object to be SM top, but it is not fully verified!

• LHC/FLC must verify charge, spin, top-gauge couplings, CKM $V_{tb}$, ...

• In general, any new physics has some observable effect on top:
  → rare decays
  → FCNC production
  → altered couplings to $Z$, $W$, $\gamma$, $g$
  → richer Yukawa structure

• Even if no new physics directly in top, must understand SM top far better, as a bkg to new physics